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A CONCEPTUAL STUDY OF THE SSV/GN&C SYSTEM DATA BUS

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16. Abstract

The development of a time-shared data bus concept compatible with the SSV/GN&C System functional and operational requirements is reported. The concept evolves from discussion, tradeoffs, and analysis presented under three basic subjects:

- o System Data Requirements
- o Data Management Considerations
- o Data Communication Techniques.

Data requirements for the SSV mission are estimated. Data classes are developed to facilitate their management and transfer. Communication techniques are evaluated to obtain an acceptable data reliability for a minimum hardware constraint. Specific recommendations of data bus features and technical characteristics are stated. A data bus interface assembly is proposed.

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1. INTRODUCTION

Inherent advantages arising from a common bus for transfer of data between systems has led to their increased use on aerospace vehicles. In addition to probable physical reductions in weight, volume, and power, a data bus offers potential advantages that include flexibility to additions or modifications of vehicle systems, standardized systems interfaces, and improved reliability arising from fewer interconnecting wires. The latter qualities were termed 'potential' since they are constrained by the capability designed into the data bus. In this sense, it is a fortunate circumstance that the SSV is presently in a conceptual state and not well defined. Concurrent conception and development of the SSV data bus precludes the possibility of a tailor-made data bus tied to a rigid system structure. Instead, the data bus capability must be based on general requirements, a general knowledge of spacecraft systems, and the types of signal data likely to be transferred. Such a basis will result in a responsive and flexible data bus system.

General requirements of the SSV data bus were stated by the Space Shuttle Vehicle (SSV)/Electronics Integration Task Team in the form of ground rules, constraints, and guidelines (Ref. 1). Requirements relevant to the data bus as extracted from the reference consist of:

- "Commands for operation of the spacecraft system shall be executed by a redundant time-shared data bus system. ... "

- "Systems will utilize, where possible, automatic in-flight isolation and system safing with manual override. ... "
- "Built-in status and test capability will apply to GSE as well as spacecraft subsystems."
- "The prime mode of sequencing and configuration moding shall be automatic, but capability shall be provided for override by the flight crew."
- "Standardized electronic interface systems shall be developed that interface with a standardized redundant multiplex data bus system."
- "Electronic systems should be designed to fail operational after failure of the two most critical components and to fail safe after the third failure."
- "Subsystem performance evaulation shall utilize operational stimuli whenever possible. ... "

In essence, these general requirements can be summarized for the data bus as follows:

1. A redundant, time-shared data bus system shall be used for transfer of all SSV system data.
2. A standard electronic assembly shall interface between the data bus and all users.
3. The data bus and standard electronic assembly shall have the following inflight capability:

    a. self-testing with operational stimuli
    b. generate operational status signals

c. automatic failure isolation and system safing by re-configuration subject to crew override

d. a fail operational-fail operational-fail safe performance.

The extensive requirements for status monitoring and fault detection, isolation, and re-configuration applies to all systems. Hence, the data bus must accommodate the large quantity of data characteristic of these housekeeping functions as well as the basic functional mode, command, and measurement data. Specific data requirements involves consideration of many complex and dependent factors pertinent to the operational and functional elements of each SSV system. The reported study pertains to the conception of a GN & C System data bus; an integral part of the SSV data bus system.

A conceptual study of a suitable data bus is a complex task. The data bus will be an application of existing communciation techniques and can be treated solely as a communication problem. This approach would probably impose constraints on or perhaps compromise the GN & C System capability. The implicit requirement for a data bus that is subordinate to and compatible with the GN & C System suggests an alternate approach. The approach would isolate and separately consider those factors dependent on the GN & C System from those factors dependent on data bus operation. The purpose of the data bus is to provide a vehicle for transfer of specific data at particular rates during certain mission operations. Thus, the data, data rates, and flexibility are dictated by the GN & C System. The technique used to transfer the data is a communication problem, where the desire for reliable and error free data transfer will be compromised by hardware requirements and the operating environment.

The report has been organized for detailed treatment of these separate factors, their combined effect, and a compatible solution. The objectives of this report were:

- Investigate GN & C System data requirements
- Determine required communication characteristics of the data bus.
- Evaluate communication techniques compatible with the GN & C System requirements
- Recommend a data bus mechanization for the GN & C System.

Section 2 reports the data requirements which define a baseline system. The investigation considers factors dependent on the GN & C System such as: mission phases, system functions, probable system mounting locations on the vehicle, an operational philosophy, classes of data, estimates of word size, the quantity of data and data rates. The estimates are compared with signal lists prepared for the Apollo/LM spacecraft.

Section 3 considers the data management interface between GN & C System units and the data bus. This phase of the study considered the baseline system, the control and flow of data, address structures and their efficiency, data frame format, and special data control signals.

Section 4 evaluates the capability of various communication techniques to provide an acceptable error rate. The acceptable error rate is computed from stated criteria. The performance expected of different signalling and error control techniques on Gaussian and noise burst channels is presented. Carrier systems and baseband systems are discussed relative to the EM environment to qualify the selected technique. A method of multiplexing the data and auxiliary signals is proposed.

Section 5 summarizes the principal study results. Specific recommendations of preferred data bus techniques and requirements are enumerated. A standard data bus interface assembly consistent with the recommendations is presented. Issues that were not satisfactorily resolved or addressed in this study that require future attention are indicated.

2. GN & C SYSTEM DATA REQUIREMENTS

This section will be concerned with identification and discussion of those factors dictated by the GN & C System and its operations that have impact on a data bus. These factors generally relate to data volumes and data rates since the data bus serves only as a vehicle for the transfer of data. The concern will focus on the diverse and variable nature of the data and its transmission rate with respect to mission and system operations. The objective of this concern will be to organize the GN & C data to facilitate its management and transfer in an efficient and practical manner by a data bus system.

2.1 GN &C System Functions

The SSV avionics performs a variety of functions during orbital or atmospheric operations. The scope of the SSV mission and subsequent complexity of the avionics required to perform the mission has motivated interest in an integrated avionics system. A substantial move to integrated avionics can be realized through use of a common data bus to service each system unit. A published functional diagram of a candidate integrated system is presented in Figure 1. (Ref. 2) The key elements in the proposed system are the two central computers titled with their primary program functions. The computers are primary users of the data bus by virtue of their substantial role in all facets of system operation. In fact, data requirements of the GN & C system have resulted in consideration of a computer

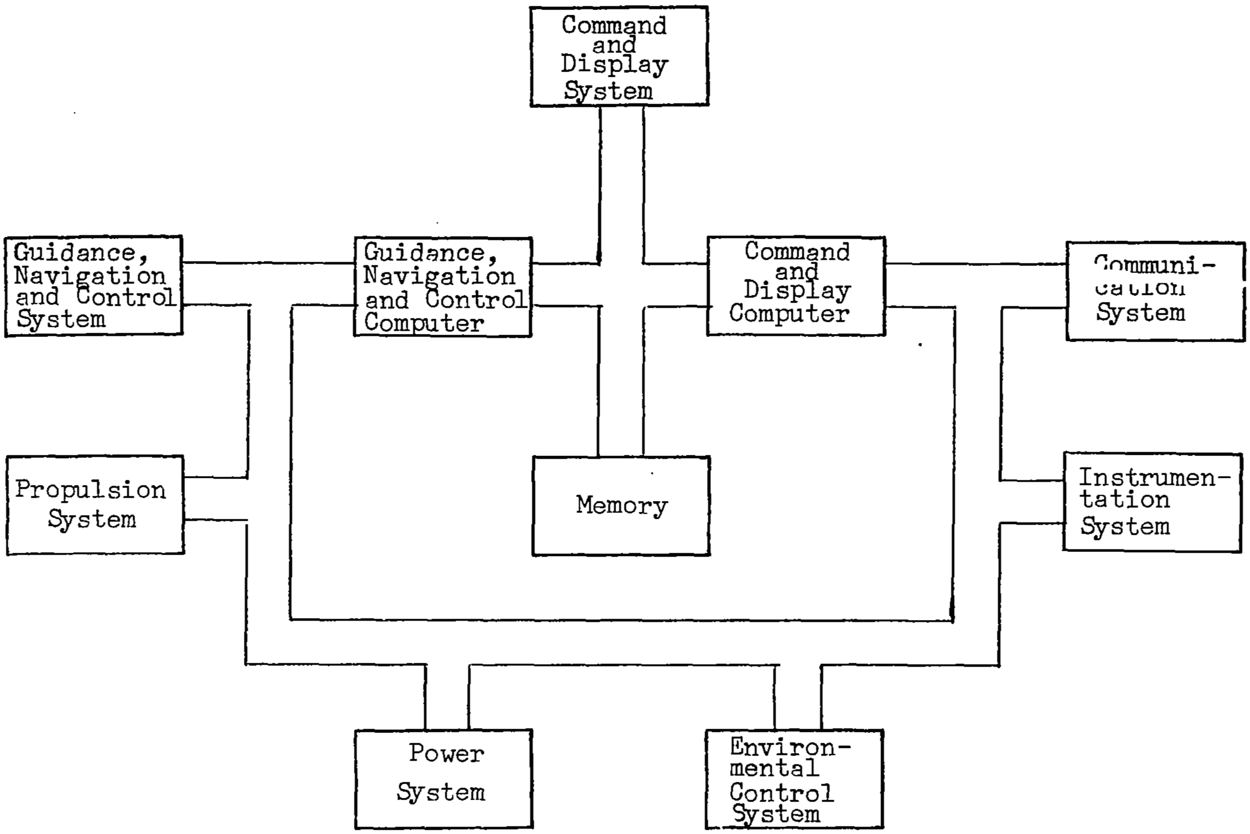


Figure 1.- Candidate SSV avionics system (Ref. 2).

or at least a data processor dedicated to this purpose. A dedicated GN & C computer or data processor allows treatment of its data bus as a separate entity. A data bus developed for dedicated service to the GN & C system would have sufficient flexibility to accommodate either a centralized or a dedicated computer system with modifications limited to data bus capacity and address structures. Consequently, the remainder of this report will assume a dedicated data bus for the GN & C system.

A GN & C system performs a number of functional operations categorized as combinations of sensing, computation, and control. 'Sensing' refers to measurements of actual vehicle state from phenomena which are independent of the computation and control functions. 'Computation' refers to processing sensed vehicle state with respect to a reference state to determine required changes in vehicle state. The 'control' function effects required changes in vehicle state by generating actuator state commands for appropriate actuators in accord with their actual states. These functions are illustrated in Figure 2. The sensors and actuators employed are dependent on primary flight variables and critical parameters encountered in the mission subject to technological constraints in measuring or effecting control of these quantities.

A reasonable complement of sensors for the SSV mission is illustrated in Figure 3. The basic functions of each system are obvious and will not be discussed. Topics of interest to the data bus are the system operational modes, the number of individual units that comprise each system, and the number and types of signals for each unit.

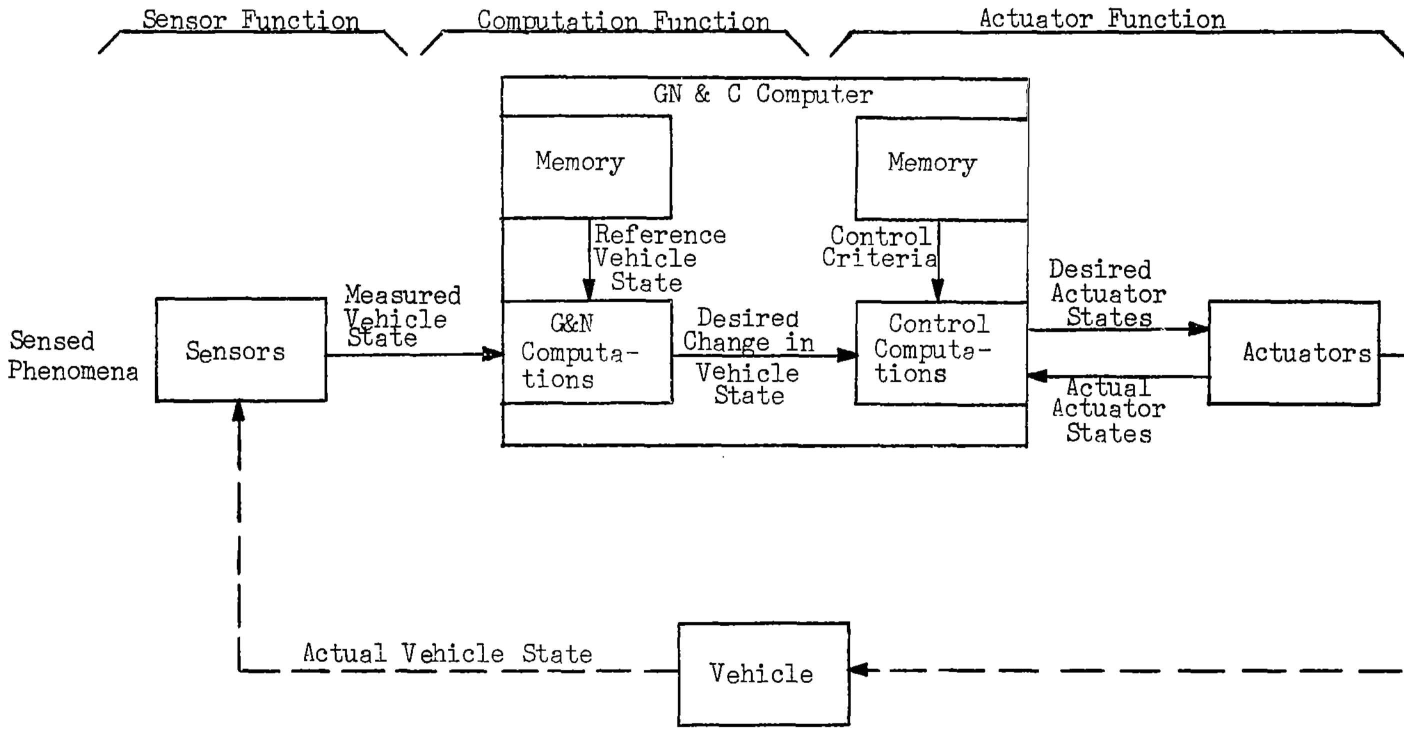


Figure 2.- GN & C system functional block diagram.

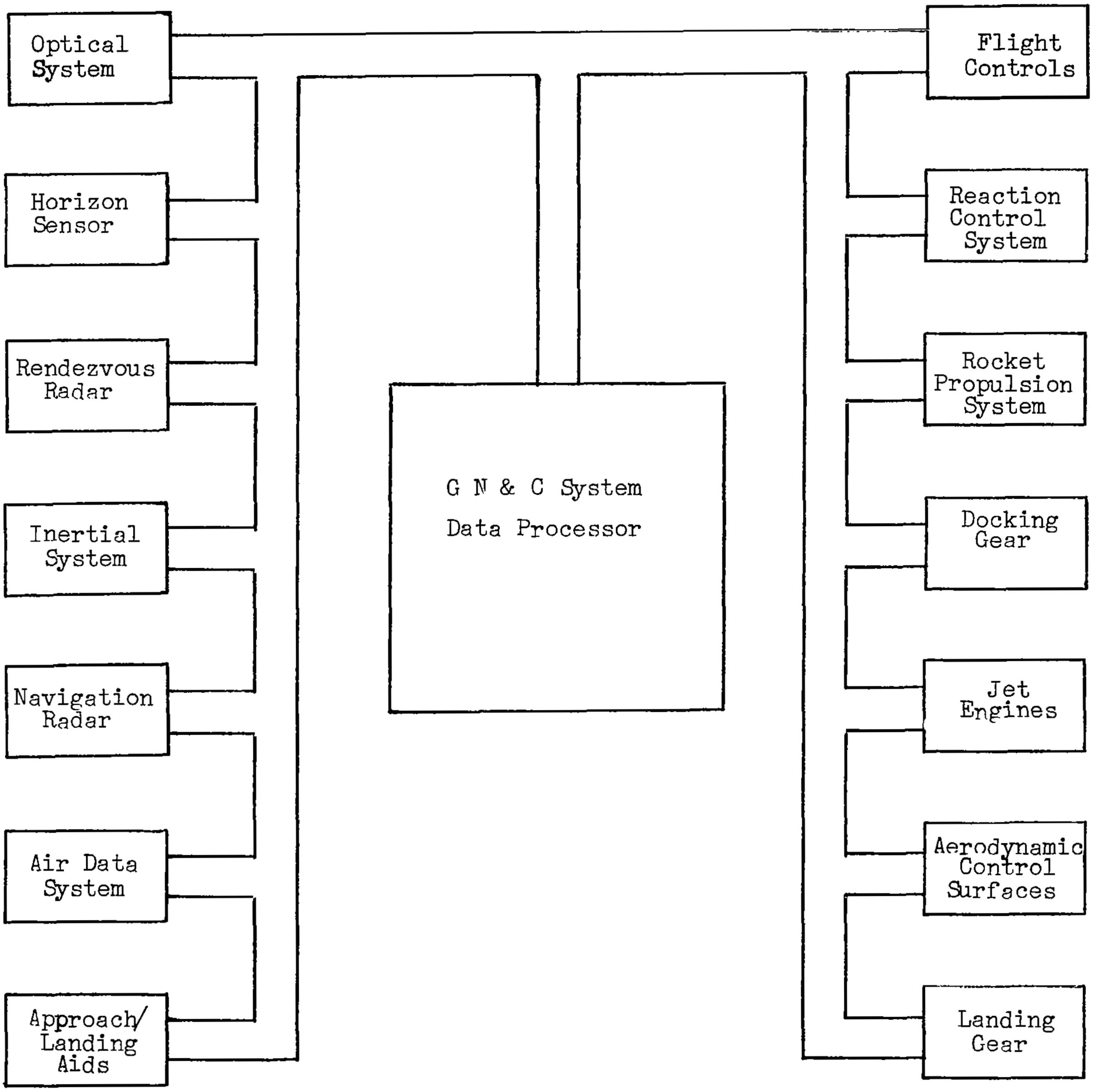


Figure 3.- Candidate GN & C system.

Table 1 lists system operation by mission phase. In terms of active systems, the entry and transition phase will require the largest number of 'on-line' systems. Otherwise, the 'on-line' systems will be about half the total and characteristic of either orbital or atmoshperic flight. Continuous operation of the inertial system, computer, and flight controls will be required. The table also indicates a near balance in the total number of active sensor systems in relation to actuator systems.

2.2 System Location on the SSV

Although each system has a unique function, it could consist of individual and separate units due to its function or the use of redundant systems. A likely location of these system units was inferred from reported studies. (Ref. 3 and 4) Figure 4 indicates the physical location of system units on the MSC orbiter vehicle. The exclusive location of sensor units in the nose portion of the vehicle is noted whereas actuator units will be in the nose, central, and tail regions. Recognition of these locations coupled with the basic GN & C functions resulted in proposed use of a dual redundant data bus: a sensor-computer data bus, and an actuator - computer data bus. (Ref. 5) Although the referenced dual data bus offers certain advantages, it will not be considered further in this report.

Figure 4 lists 45 separate system units; 8 sensor units, 1 computer unit, and 36 actuator units. A minimum amount of cabling would be realized by routing the data bus to each of these units and treating each as individually addressable units. An alternative

TABLE I.- SYSTEM OPERATION BY MISSION PHASE

	Pre-launch (All Data)	Launch	Orbit Determination	Rendezvous	Station Keeping	Docking	Entry and Transition	Cruise	Landing	Conventional Take-off	Number of Active Phases (10 Total)
Optical System	X		X	X			X				4
Horizon Sensor	X		X		X		X				4
Rendezvous Radar	X			X	X	X					4
Inertial System	X	X	X	X	X	X	X	X	X	X	10
Navigation Radar	X		X				X	X	X	X	6
Air Data System	X	X					X	X	X	X	6
Approach/Landing Aids	X								X		2
Computer	X	X	X	X	X	X	X	X	X	X	10
Flight Controls	X	X	X	X	X	X	X	X	X	X	10
Reaction Control System	X	X	X	X	X	X	X				7
Rocket Propulsion System	X	X		X			X				4
Docking Gear	X					X					2
Jet Engines	X						X	X	X	X	5
Aerodynamic Control Surfaces	X						X	X	X	X	5
Landing Gear	X								X	X	3
Number of Active Sensor Systems (7 Total)	7	2	4	3	3	2	5	3	4	3	
Number of Active Actuator Systems (7 Total)	7	3	2	3	2	3	5	3	4	4	
Number of Active Systems (15 Total)	15	6	7	7	6	6	11	7	9	8	

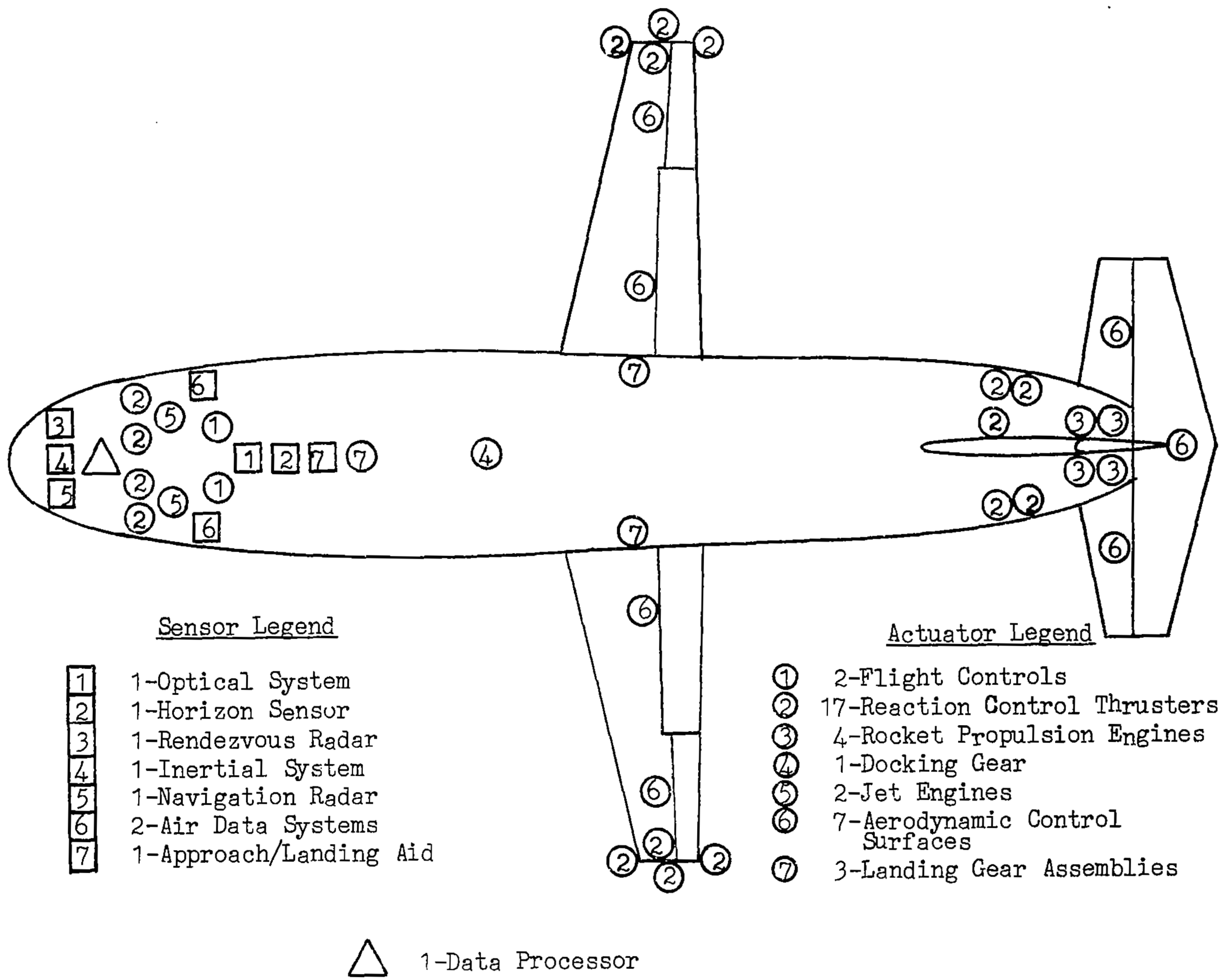


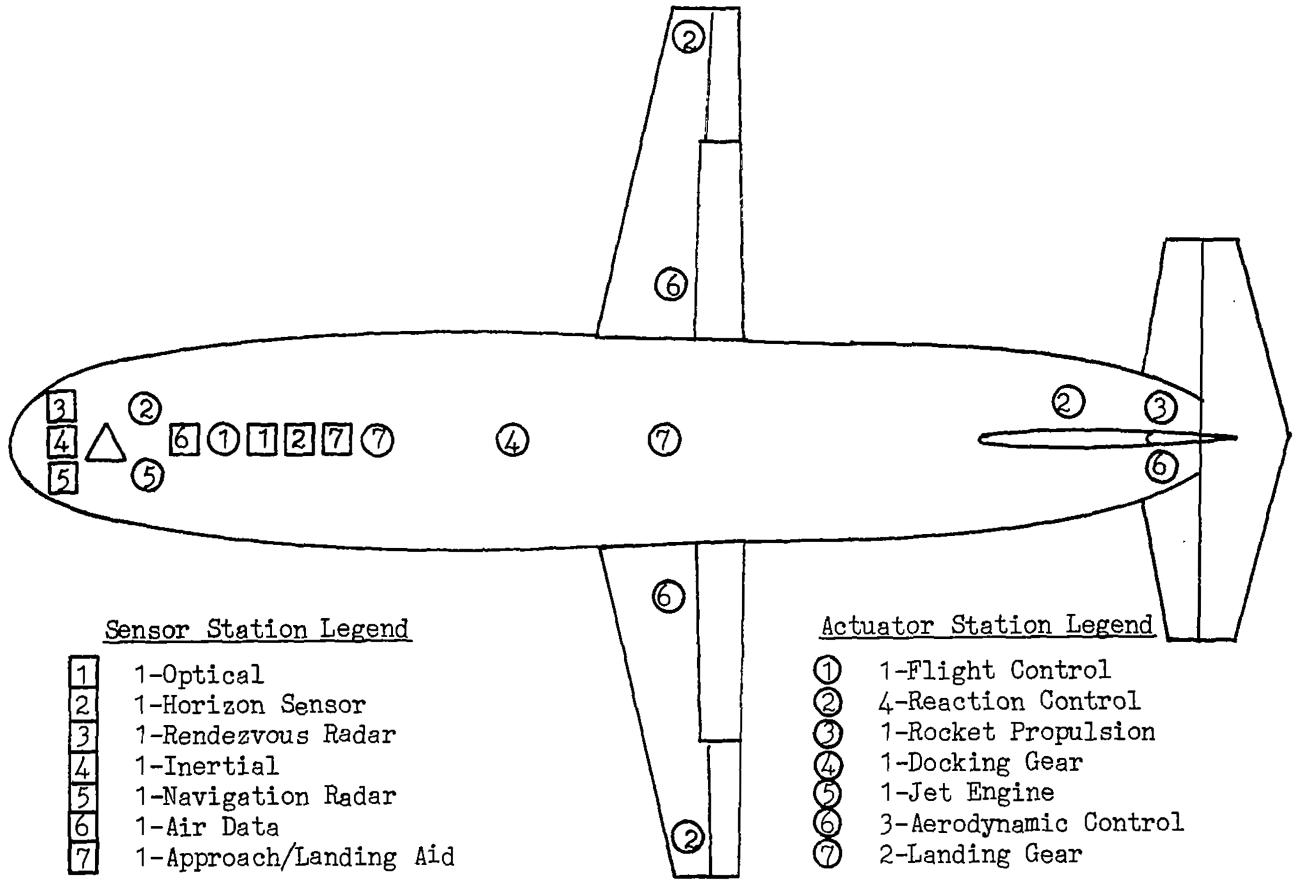
Figure 4.- Candidate location of GN & C system units on MSC orbiter vehicle.

would be to group units of the same system by their physical location with each group treated as an individually addressable station. This alternative is illustrated in Figure 5 and would require only 20 addressable stations: 7 sensor units and 13 actuator units. The reduction of addressable units was realized by the grouping of reaction control thrusters, aerodynamic surfaces, and rocket engines as shown. The alternative reduces the number of interface - local processor assemblies required at the expense of routing short cable assemblies from the common local processor to each unit operating from the station. The net reduction in active components realized by the unit stations is desirable and will be assumed in the remainder of this report.

The number and types of signals for each station are difficult to establish with precision due to the dependence on and subsequent assumptions regarding a variety of system considerations. The remainder of this section is devoted to this subject.

2.3 Operational Data

Although the reasons for employing a particular system is beyond the scope of this report, the system operating signals are of prime importance. These operational signals convey either functional data or housekeeping data. Characteristics of these data are dependent on the specific system techniques and hardware employed. With these systems in a conceptual state, the characteristics must be estimated. Reasonable estimates can be obtained by



<u>Sensor Station Legend</u>

1 1-Optical
2 1-Horizon Sensor
3 1-Rendezvous Radar
4 1-Inertial
5 1-Navigation Radar
6 1-Air Data
7 1-Approach/Landing Aid

<u>Actuator Station Legend</u>

1 1-Flight Control
2 4-Reaction Control
3 1-Rocket Propulsion
4 1-Docking Gear
5 1-Jet Engine
6 3-Aerodynamic Control
7 2-Landing Gear

△ Data Processor (Not addressable)

Figure 5.- Addressable unit stations.

extrapolating system data obtained from Apollo hardware manuals and the general literature to fit the needs of the SSV. Certain system development options presently being studied elsewhere will be briefly discussed to form a basis for the data estimates.

The SSV will undoubtedly employ the techniques and an updated generation of hardware which proved successful in the Apollo program. Items of particular significance to the data bus were the reliable "fly-by-wire" operation and the extensive computer activity in fault detection, system safing, and display computations. The SSV requirements in Reference 1 express an increasing volume of computer activity for fault detection, isolation, and reconfiguration. These auxiliary computer activities have considerable impact on the data bus as discussed below.

A typical system unit requires perhaps from 8 to 16 basic functional signals: 5 to 10 mode control signals and 3 to 6 input and/or output signals. These signals characterize the composite output or action of many components as well as the measurable or controllable quantities. The purpose of fault activities is to maintain confidence in operational integrity, to prevent unsafe conditions from occuring or at least persisting, and to provide information for fault circumvention.

Fault activities are usually discussed in terms of detection, isolation, and correction. Fault correction, as used here, signifies disabling of the failed component and enabling redundant components to maintain the initial capability. These activities require descriptive information on components, component assemblies, sub-assemblies, units, and systems. The permutations of faults increases rapidly forcing a compromise in fault tolerant capability. The level of compromise is related to the amount of hardware and computer capacity allocated to this function. With computer access via a data bus, the data bus capacity represents an ultimate limit on the rate of information available to the computer or crew for fault activities. The limit can be increased by processing fault signals within each system and communicating only the processed results over the data bus. (The processed results possess more information content than the "raw" unprocessed data which increases the "symbol" information rate, according to information theory.) The central processor would evaluate this information weighed by similar information from other on-line systems to maintain an overview of vehicle operation.

The existence of a processor within each system may be necessary for reasons other than the data bus. These "local processors" may in fact be small digital computers in the complex optical and inertial systems and perhaps the jet engines. In addition to the operational and technical advantages of local processors, contractural interfaces are explicitly defined since the systems contractor must solve the unique computational needs of that system. The existence of local processors substantially reduces expected interface data between the systems and central computer, particularly for fault activities.

If local processors develop into small scale digital computers, the need could arise for transfer of an erasable memory. Since these data would be infrequently communicated, the additional demands on the data bus would be readily accommodated.

With this background, the operational data will be estimated relative to the typical station structure illustrated in Figure 6. The basic elements of the structure consist of 1) a standard interface, 2) buffer storage, 3) a local processor, and 4) the basic system or unit components. Note that neither unit grouping or redundant components are shown. The data bus and standard interface serve as a vehicle for the transfer of all signals into and out of a unit. The buffer storage serves as temporary storage of these signals to avoid synchronous unit operation and provide data on demand without local interrupts. The local processor interfaces all signals as required and serves as a local authority on unit operation. The unit simply executes the commands issued by the local processor. These commands include failure isolation and correction by power switching. Additional discussion of other details on Figure 6 is deferred until later. The interest here is the organization of all possible data into descriptive classes for efficient data management and transfer. The organization will also facilitate estimates of system data rates and provide insight on the distribution and usage of data classes.

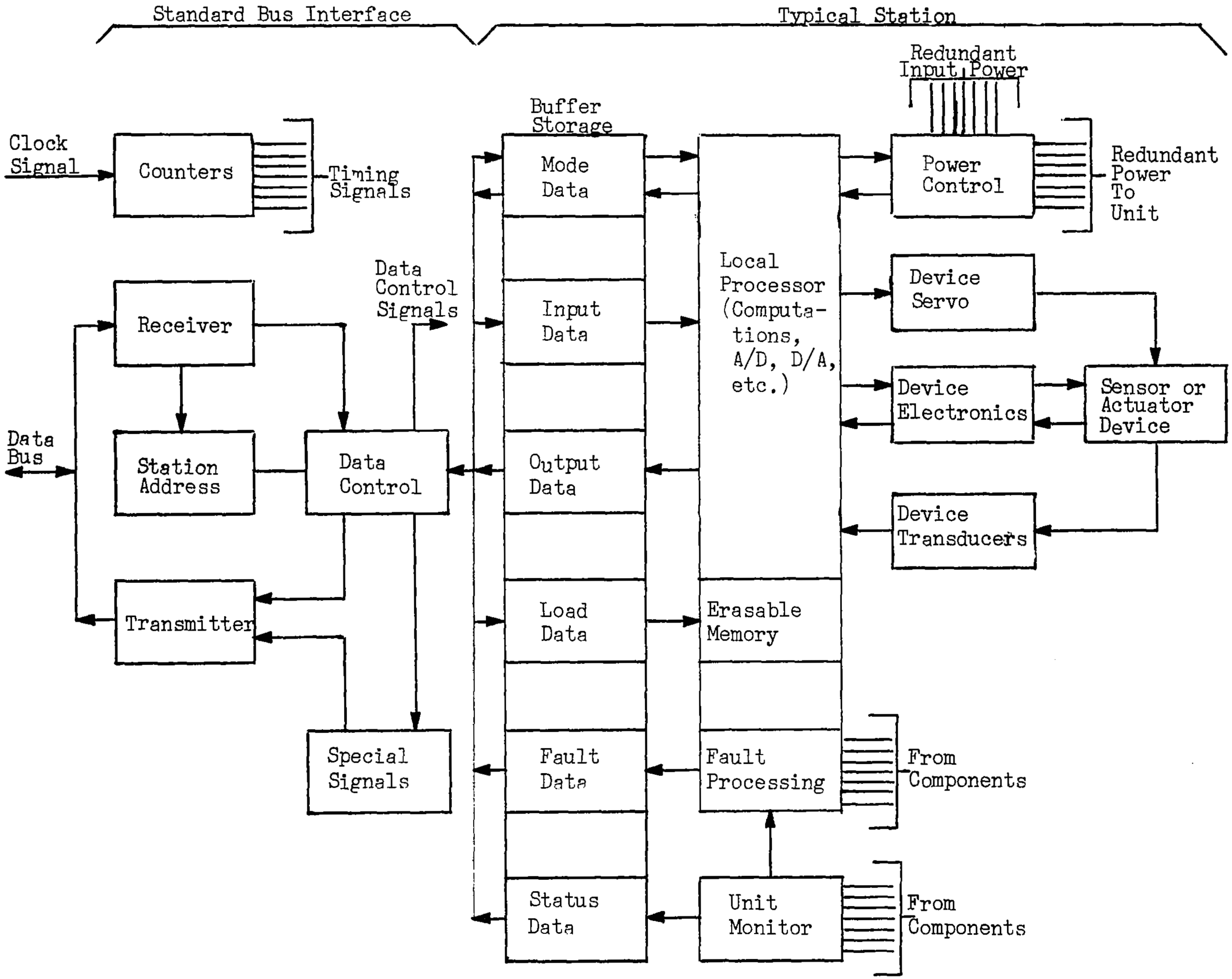


Figure 6.- Typical GN & C station structure.

2.4 Classes of System Data

The primary motivation for organizing system data into classes can be attributed to the advantages in data management and transfer. Various classes of data inherently exist within the GN & C System. Identification of unique classes provides the means for resolving such areas of concern as data bus compatibility, flexibility, and efficiency. In addition, the classification standardizes the data peculiar to any or all systems with minimal address requirements internal to a station as demonstrated in Section 3. These desirable attributes are clearly dependent on the choice of signal classes. The choice must reflect data rates since data bus capacity represents a basic and ultimate limit.

The operational data was previously discussed in terms of functional data and housekeeping data. Consideration reveals the functional class to be of low to moderate data volume and high data rates while the housekeeping data will be of moderate to high volume and require relatively low data rates. These class distinctions are characteristic of a system but do not differentiate between the inherent needs of different systems. The needs of each system will be emphasized by division of the functional data into mode, input, and output classifications along with division of the housekeeping data into status, fault, and load classifications. These classes are defined as follows:

<u>MODE</u>: Digital words composed of discretes that 1) commands or designates the mode of system operation, 2) flags output signal data, 3) flags internal faults, and 4) controls unit power.

INPUT: Basic functional digital data required by the unit or system that originates elsewhere.

OUTPUT: Basic functional digital data originated within the unit or system that is required elsewhere.

STATUS: Normal operational housekeeping digital data originated within the unit or system for display elsewhere.

FAULT: Failure data originating within a unit or system that indicates 1) the isolated area, 2) the suspected component, and 3) the internal corrective action for crew and/or computer evaluation or override.

LOAD: Erasable memory constants for the local processor that originates by crew input, central computer memory, or uplink data.

These data classes are inclusive of all possible system data, relate directly to system data rates, and distinguish between data used exclusively within the GN & C system from that generated within the GN & C system for external use. The contention that these classes possess the desired qualities will be supported by a discussion of their use.

The MODE data will consist of a couple of digital words per station at most. These data provide central control of vehicle configuration, go/no-go type information on the operation and integrity of the unit or system, and the capability for external crew aided fault isolation and correction. The low volume, high information content of this data provides rapid alerts to the central computer of changes in system or unit status.

The distinction between INPUT and OUTPUT data provides for independent transfer of these data to accommodate different systems. For example, sensor systems generally require designated INPUT data only for initializing conditions and provide measured OUTPUT data thereafter. In contrast, an actuator system receives INPUT commands and feedsback current actuator states via OUTPUT data for the next computation cycle. The MODE, INPUT, and OUTPUT data comprise all functional data required for routine system operation.

The STATUS information pertains to routine operation but need be transferred only when a useful change in data has occurred. The central computer will be informed of this event by the status signal flag discretes in the MODE data. Upon reception of the status flag, the central computer can call the STATUS data immediately or assign the event (and unit) a priority for later call dependent on other computer activity. This feature acts as a local editor of the low information content, and slowly varying signals in the STATUS classification. The feature still allows routine scheduling and transfer of these data upon call from the central computer.

The fault correction flag discretes in the MODE data function similar to the status flag discretes. The fault flag discretes inform the central computer of any unit fault activity by assignment of a priority related to the fault consequences. The fault flag discretes will be retained in the MODE data until specific central computer reset commands are received. In the interim period, the central computer relays the fault priority and unit address to the crew display, assesses the fault priority in relation to other activity, and eventually calls FAULT data for computer and crew evaluation. If the unit fault correction resolved the difficulty to crew satisfaction, the corrective action and associated components are recorded and the failure flag discretes are reset by crew action. If the unit correction was inadequate, ineffective, or unsatisfactory to the crew, external fault evaluation and correction will be provided by the power control discretes in the MODE data with results of each action inherently contained in the STATUS and FAULT data available on call. The crew activity persists until the problem is resolved and a fault flag reset command is received.

The LOAD data anticipates the need for an erasable memory in the local processor as previously discussed. The data will be infrequently communicated and does not impose a problem to the data bus.

The preceding discussion demonstrates utility of the six classes of data and local status and failure editing. The net effect of this organization was to reduce time occupancy of the data bus by communicating data on the basis of need as determined at the central and local levels. The existence of a time varying need arising from vehicle activity, various combinations of functional data, random failures, etc., will be compatible with the outlined system and data bus operation. Further evaluation will be presented based on estimates of the data volume and data rates of each system.

2.5 Estimates of System Data Rates

Estimates of GN & C system data were obtained by considering the basic functional operation, the functional data signals, and speculating on the number of status signals required for each system. Additional data were included for those systems with separate units, as previously discussed. The estimates derived from this procedure are listed in Table 2. FAULT and LOAD data were not included since they will be infrequently communicated and not significantly affect the data rate. It should be noted that two words were included in each INPUT and OUTPUT data for registering of a "time to go" and an "elapsed time" which will be discussed in paragraph 2.8.

The percent of the total words represented by the entry for each row and column were included for comparison. The volume of data is virtually balanced between sensors and actuators for all entries. The STATUS data entries exceed the functional entries for each system. The functional data constitutes 40% of the total data. Equivalent data for Apollo/LM was determined to be 44% of the total as reported in Appendix A.

If FAULT and LOAD data were included, the functional data would total from 20 to 30% of all data. Since the MODE data constitutes only 7% of the total data, it will provide an efficient means of central control and awareness by reducing data bus time occupancy.

The quantity of data required for each mission phase was obtained through combination of the estimated data words per system

TABLE II.- ESTIMATED DATA WORDS FOR EACH SYSTEM

SENSOR SYSTEMS	Mode Words	Input Words	Output Words	Func-tional Words	Status Words	Total System Words	% of Total Words
Optical	8	14	16	38	60	98	11%
Horizon Sensor	2	6	7	15	20	35	4%
Rendezvous Radar	4	6	7	17	20	37	4%
Inertial	8	11	16	35	80	115	13%
Navigation Radar	4	8	10	22	30	52	6%
Air Data System	2	6	9	17	20	37	4%
Approach/Landing Aids	8	7	10	25	60	85	10%
Total	36	58	75	169	290	459	53%
ACTUATOR SYSTEMS							
Flight Controls	10	-	14	24	60	84	10%
Reaction Control	4	34	-	38	40	78	9%
Rocket Propulsion	1	20	20	41	40	81	9%
Docking Gear	1	-	-	1	2	3	0%
Jet Engines	4	16	20	40	40	80	9%
Aerodynamic Control Surfaces	3	8	8	19	30	49	6%
Landing Gear	2	6	6	14	20	34	4%
Total	25	84	68	177	232	409	47%
GN & C SYSTEM	61	142	143	346	522	868	100%
% of Total Words	7%	16%	16%	40%	60%	100%	

(Table 2) with all active systems for each mission phase (Table 1). The results are presented in Table 3. The prelaunch phase column includes all data and was used as a reference for other mission phases. The entry and transition phase requires 82% of the total data to accommodate the simultaneous need for operation of orbital equipments and the standby state of atmospheric equipments. Landing will be the second most active phase requiring 62% of the total data, also divided equally between sensors and actuator systems. The estimated data volume varies with mission phase from 37% to 82% of the total system data.

The data volumes of Table 3 were used to estimate the data rates of Table 4. These estimates were obtained by employing the sampling rates characteristic of Apollo systems for each data type (Ref. 6). Thus, all functional sensor system data were assumed updated at 1 sample/second with the actuator system data updates at 10 samples/second. All STATUS data were assumed updated at 1 sample/2seconds. Note that the sampling rates can represent an average rate for the data of each class. The system data rates were calculated for word lengths of 20 bits and 25 bits to provide some indication of sensitivity to word length. The additional 5 bits can be considered representative of total address requirements. On a percentage basis, the additional 5 bits will be insignificant.

A maximum data rate of 55KBPS was obtained from the procedure outlined. The entries of Table 4 show the data rate to vary from

TABLE III.- ESTIMATED GN & C SYSTEM DATA WORDS BY MISSION PHASE

	Prelaunch (all data)	Launch	Orbit Determination	Rendezvous	Station-keeping	Docking	Entry and Transition	Cruise	Landing	Conventional Take-off
Sensor Systems:										
MODE	36	10	22	20	14	12	24	14	22	14
INPUT	58	17	39	31	23	17	45	25	32	25
OUTPUT	75	25	49	39	30	23	58	35	45	35
Functional Data (Sub-total)	169	52	110	90	67	52	127	74	99	74
Status Data (Sub-total)	290	100	190	160	120	100	210	130	190	130
Actuator Systems:										
MODE	25	15	14	15	14	15	22	17	19	19
INPUT	84	54	34	54	34	34	78	24	30	30
OUTPUT	68	34	14	34	14	14	62	42	48	48
Functional Data (Sub-total)	177	103	62	103	62	63	162	83	97	97
Status Data (Sub-total)	232	140	100	140	100	102	210	130	150	150
Total: Functional Data	346	155	172	193	129	115	289	157	196	171
Status Data	522	240	290	300	220	202	420	260	340	280
All Data	868	395	462	493	349	317	709	417	536	451
% of Total Words	100%	46%	54%	57%	41%	37%	82%	49%	62%	52%

TABLE IV.- ESTIMATED GN & C SYSTEM DATA RATES BY MISSION PHASE

	Prelaunch (All data)	Launch	Orbit Determination	Rendezvous	Station-keeping	Docking	Entry and Transition	Cruise	Landing	Conventional Take-off
Functional Data Words: Sensor Systems	169	52	110	90	67	52	127	74	99	74
Actuator Systems	177	103	62	103	62	63	162	83	97	97
Status Data Words:	522	240	290	300	220	202	420	260	340	280
Data Rates For 20 Bit Words: Sensors (1 sample/second)	3.38K	1.04K	2.20K	1.80K	1.34K	1.04K	2.54K	1.48K	1.98K	1.48K
Actuators (10 samples/second)	35.40K	20.60K	12.40K	20.60K	12.40K	12.60K	32.40K	16.60K	19.40K	19.40K
Status (1 sample/2 seconds)	5.22K	2.40K	2.90K	3.00K	2.20K	2.02	4.20K	2.60K	3.40K	2.80K
Total Bits/second	44.0 K	24.0 K	17.5 K	25.4 K	15.9 K	15.7 K	39.1 K	20.7 K	24.8 K	23.7 K
Data Rates for 25 Bit Words: Sensors (1 sample/second)	4.23K	1.30K	2.75K	2.25K	1.68K	1.30K	3.18K	1.85K	2.48K	1.85K
Actuators (10 samples/second)	44.25K	25.75K	15.50K	25.75K	15.50K	15.75K	40.50K	20.75K	24.25K	24.25K
Status (1 sample/2 seconds)	6.52K	3.00K	3.62K	3.75K	2.75K	2.53K	5.25K	3.25K	4.25K	3.50K
Total Bits/second	55.0 K	30.1 K	21.9 K	31.8 K	19.9 K	19.6 K	48.9 K	25.9 K	31.0 K	29.6 K
% of Maximum Rate	100%	55%	40%	58%	37%	36%	89%	47%	57%	54%

36% to 89% of the maximum rate as a function of mission phase. The relative demands of each mission phase are similar when compared on the basis of data volume to those of data rates.

The 55KBPS data rate is as valid as the assumptions required to obtain the estimate. The most sensitive assumptions were the sampling rates. The 10 sample/second rate assumed for all functional actuator data was predicated on the use of a digital auto-pilot where the data signals occur within the control loop. The assumed sampling rate would be sufficient for control bandwidths up to perhaps 3 Hz, a reasonable value. If these arguments are not applicable, the data rates would be substantially reduced. For example, if all data were arbitrarily assumed transferred at a 1 sample/second average rate, a 25 bit word would require a maximum rate of only 21.7 KBPS. In contrast, Reference 2 states a 30KBPS data rate for the GN & C system based on "conservative assumptions and large factors of safety".

The maximum expected system data rate is critical only if it approaches data bus capacity. In addition to the GN & C system dependent data, Section 3 will discuss the data required for address and redundant transmissions. These additional data will require an increased bus capacity. The use of a 1MBPS signalling rate will provide a capacity in excess of any conceivable situation except 'raw' sensor data processing. The use of local processors for such processing eliminates this situation. Hence, a 1MBPS signalling rate will eliminate concern for a precise knowledge of system data rates or their uncertainty.

2.6 Comparison of Data Estimates with Apollo/LM

A detailed study of GN & C System signals was conducted for the Apollo/LM spacecraft. (Ref. 7) Signal lists were compiled for all GN & C assemblies of LM-4 from Level 3 drawings prepared by Grumman Aircraft Engineering Corporation. The detailed lists are included in this report as Appendix A. The LM assemblies were arranged into systems for comparison with corresponding SSV systems. Table 5 lists the data words tabulated for a LM spacecraft assuming use of a data bus. The SSV estimates compare reasonably well except for the Optical and Flight Control systems. The discrepancy between Optical systems was expected from the more complex requirements on the SSV. The unfavorable comparison between the Flight Control listings is due to the inclusion of display data in the LM tabulation while including such data in the SSV STATUS class. Using LM data as a base, the comparison indicates the SSV data estimates to be reasonable, but may be low.

An additional check on estimated data volume was obtained from Reference 8 which contains a tabulation of the quantity of measurement types in LM-4. The tabulation does not distinguish between measurements used exclusively within a system and those for external use. Hence, it is not known if all measurements were intersystem signals. The information seems to be useful and is presented in Table 6. It is interesting to note that 609 of the 1128 total measurements (54%) were performed within the GN & C System. These measurements include functional and housekeeping data and should provide a rough comparison with corresponding SSV estimates. By eliminating the 122 discrete events, the remaining 487 measurements should

TABLE V.- COMPARISON OF DATA WORDS BETWEEN EQUIVALENT LM SYSTEMS AND SSV SYSTEMS

SYSTEM	LM Mode	LM Input	LM Output	LM Status	SSV Mode	SSV Input	SSV Output	SSV Status
Optical	1	-	2	-	8	14	16	60
Horizon Sensor[a]								
Rendezvous Radar	2	2	19	7	4	6	7	20
Inertial	2	18	23	7	8	11	16	80
Navigation Radar[b]	2	-	6	8	4	8	10	30
Air Data System[a]								
Approach Landing Aids[a]								
Flight Controls	13	59	44	18	10	-	14	60
Reaction Control	6	28	7	66	4	34	-	40
Rocket Propulsion	8	41	20	64	1	20	20	40
Docking Gear[a]								
Jet Engines[a]								
Aerodynamic Control Surfaces[a]								
Landing Gear[a]								
Totals:								
Class	34	148	121	170	39	93	83	330
Functional	303				215			
Housekeeping	170				330			
Operational	473				545			

NOTES: (a) No equivalent LM system.
(b) LM Landing Radar Data

TABLE VI.- QUANTITY OF MEASUREMENT TYPES IN LM-4

MEASUREMENT	G & N	C.E.S.	A.G.S.	A.E.	D.E.	R.C.S.	RADAR	GN & C TOTAL	Electrical Power System	Environmental Control System	Scientific Equipments	Mechanical Design	Communication System	Pyrotechnics	LM TOTAL
Voltage	35	77	41	2	12	53	61	281	42	8	93		13	18	455
Discrete Event	3	15	41	14	12	30	7	122	31	20	42	13	2	7	237
Pressure				9	10	22		41		14					55
Combination				2		17		19	12	4	8			1	44
Temperature	2		1	6	5	8	1	23		8	1		1		33
Quantity					19			19		3					22
Frequency			4				4	8	1		8				17
Position	1		1		1		4	7					2		9
Velocity	3		3				3	9							9
Current									6				2		8
Power							5	5					2		7
Rate							2	2		2					4
Resistance/ Continuity														2	2
Phase													1		1
(Unknown)		26	26			4	17	73	27	40	58		27		225
Total	44	118	117	33	59	134	104	609	119	99	210	13	50	28	1128

approximately correspond to the total SSV data less the MODE data which amounts to 807 words. Allowing for the 9 LM GN & C systems and the 15 SSV systems, an average of 54 measurements per system will be obtained for each vehicle. Although this result is probably due to coincidence, the comparisons indicate the estimated data volume for the SSV is reasonable and consistent with the techniques employed on the LM spacecraft.

2.7 Data Word Length

The data rates were estimated for assumed word lengths of 20 and 25 bits. The SSV data word length has not been decided but will probably be larger than the 16 bits used in the Apollo Guidance Computer. The data word length within a system will be determined by measurement and computation precisions. Transfer of the data word between systems will require additional bits for addresses and data instructions. These subjects will be elaborated on in Sections 3 and 4. The interest here is to establish bounds on the magnitude of the SSV data word length for this report.

A lower bound on the SSV data length would be the Apollo word lengths. The Apollo Guidance Computer employed a basic 16 bit word: 14 magnitude bits, 1 sign bit, and one parity bit. Certain data internal to the computer was operated on in double or triple precision. Other data was transferred between the AGC and assemblies in pulse form with resolution more than that of a 14 bit magnitude data. These data included translational velocity increments, gimbal angle increments, gimbal torquing signals, and radar range measurements. Transfer of these and other data on a data bus will require a word length commensurate with the maximum value and desired resolution. Table 7 lists the dynamic range of various data words as determined from known mission requirements, physical limitations and hardware capability. For example, the least significant bit entered for coarse angle data is comparable to 3 minute synchro data. From these considerations, a data word of 20 bits would appear ample for all transferred data exclusive of address and instructions. Hence, the word lengths assumed for estimation of data rates are justified.

2.8 Timing Signals

In addition to the operational data, timing signals for clock and synchronization will likely be transferred on the data bus. The LM signals listed in Appendix A include one or more timing signals in one-third of the total intersystem signal groups. 7 of the 9 LM/GN & C systems required timing signals. These timing signals were required to strobe pulse data between systems, torque gyros, and for synchronism with the PIPA loops and power supplies. These requirements will not apply to the SSV since data will be transferred as digital PCM to a local processor that will generate the unique torquing and/or synchronizing signals of that unit. However, most methods of data transfer are not self-clocking and will require bit sync. Assuming a bit sync will be required, it can be usefully employed to coordinate events between systems as discussed below.

TABLE VII.- POSSIBLE MAGNITUDE OF DATA WORDS

DATA	Maximum Value	LSB Resolution	Data Mag-nitude	Sign	Data Mag-nitude	Comment
TIME						
Mission time	12.3days	1sec.	20B	None	20B	7 day mission
Time to go	4.3min.	.001sec.	18B	None	18B	Assumed .001 second resolution
Elapsed time	4.3min.	.001sec.	18B	None	18B	Assumed .001 second resolution
Event time	17.5min.	.001sec	20B	None	18B	Assumed .001 second resolution
ROTATION						
Coarse angle	360deg.	2.6$\widehat{\text{min}}$.	13B	1B	14B	Typical 3$\widehat{\text{min}}$. synchro data
Fine angle	360deg.	9.9$\widehat{\text{sec}}$.	17B	1B	18B	2 speed (1X and 16X) synchro data
Angular velocity	82deg/sec	.005deg/sec	14B	1B	15B	Selected gyro drift rate
TRANSLATION						
Geocentric range	8388Km	8m	20B	None	20B	2010Km orbital altitude
Orbital altitude	2097Km	2m	20B	None	20B	
Radar range	2097Km	2m	20B	None	20B	
Orbital velocity	1.04Km/sec	1cm/sec	20B	None	20B	
Stationkeeping And Docking Velocity	10.2m/sec	1cm/sec	10B	1B	11B	
ANALOG SIGNALS						
Voltage	1 unit	0.1%	10B	1B	11B	Precision analog
Current	1 unit	0.1%	10B	1B	11B	Precision analog
Resistance	1 unit	0.1%	10B	None	10B	Precision analog
Temperature	3000°C	3°C	10B	1B	11B	
Pressure	2000psi	2psi	10B	None	10B	Precision analog

A complication arising from a time-shared data bus will be the coordination of an event between two systems or stations. For example, use of optical data for inertial platform alignment requires simultaneous optical and inertial angle data readouts at a specific time to eliminate time dependent errors. A less severe problem will occur during an uncoordinated firing of thrusters which causes small but undesired translational and rotational forces due to inherent time delays. These delays can be eliminated by transferring the 'time to go' of an event and a central clock along with other data pertinent to the event to each station involved in the event. The 'time to go' and clock provide a flexible means of generating simultaneous gating signals within different stations. In anticipation of events generated within a station, an 'elapsed time' data word would also be useful in coordinating or evaluating events as well as providing a differential time for estimation or computation of derivatives and integrals of the station OUTPUT data.

A reasonable time resolution of these data words would be 0.001 seconds/bit in contrast to the AGC time resolution of 0.01 seconds. A 20 bit data word will allow up to 17.4 minutes of differential time between transfer of a scheduled event and occurrence of the event. This feature not only coordinates an event, it also eliminates the need for precise bus scheduling and frees the bus during critical events for status and fault monitoring. The expected utility of these data words led to their inclusion in each unit INPUT and OUTPUT data as stated in paragraph 2.5.

The central clock signal would be continuously supplied to all data bus stations. The clock rate would be identical to the bit rate for bit sync. Down-counters would derive the 1 millisecond timing signal and other timing signals from the clock signal within the interface assembly as shown in Figure 6. The clock signal and data signals can be multiplexed onto the data bus. An alternative technique would synchronously modulate a sinusoidal clock signal (or a clock harmonic) with the serial data stream to realize a coherent communication system in which the clock can be extracted from the modulated data signal. These possibilities will be discussed in detail in Section 4. For the present, it will be assumed that a clock and a data channel will be required to avoid undesirable delays associated with a time shared data bus.

2.9 Summary

The section was concerned with identification and discussion of GN&C System factors that have impact on a data bus. A data bus dedicated to GN&C System service was assumed to isolate its requirements from those of other SSV systems. A data bus developed for dedicated service will have sufficient flexibility for operation with either a centralized or a dedicated computer system.

A candidate GN&C System was discussed. The System was composed of 15 systems: 7 sensor systems, 7 actuator systems, and a GN&C Data Processor. These systems consist of 45 separate units located on the MSC Orbiter Vehicle. Grouping units of the same system in a common location resulted in 20 individually addressable stations. The SSV mission was categorized by 10 distinct phases with the active systems noted for each phase. The entry and transition phase will impose the greatest demands since it requires 11 active systems.

GN&C System operational data were organized into classes to obtain a standard form for data management and transfer that satisfies the needs of all systems. The total operational data were discussed in terms of functional data and housekeeping data. The proposed functional data classes were termed MODE, INPUT, and OUTPUT. The proposed housekeeping data classes were termed STATUS, FAULT, and LOAD. System operation was discussed in terms of these classes. The use of STATUS and FAULT flag discretes within the MODE data was proposed as a means of reducing data bus time occupancy by communicating data on the basis of need. These flag discretes will effectively edit the data internal to a station and alert the data processor to internal change and the subsequent need to call for these data.

Data requirements were estimated for the MODE, INPUT, OUTPUT, and STATUS data. FAULT and LOAD data were not included since they will be infrequently communicated and not significantly contribute to data rates. The data requirements were obtained by estimating the quantity of data words per system for each system class, combining these quantities for all active systems for each mission phase, and applying Apollo DAP sampling rates to the total data quantity of each class. The computations were performed for a 20 bit and 25 bit word size. The 20 bit word was shown to be sufficient for all data magnitudes by considering the dynamic range and resolution requirements of many variables. The 25 bit word was considered representative of the transferred data to include address and instruction bits. A 25 bit word will require a 55.0 KBPS signalling rate for all data. The data rate varied from 36% to 89% of the maximum data rate by mission phase with a 48.9 KBPS rate during entry and transition. The proposed 1 MBPS signalling rate will provide a capacity in excess of any conceivable situation.

The estimated SSV data was compared with equivalent data compiled for the Apollo/LM spacecraft. The comparisons indicated the estimated data quantities to be reasonable and consistent with the techniques employed on the LM.

The use of 'time to go' and 'elapsed time' words was proposed to compensate for inherent time delays in a time-shared data bus. The data would be included in each unit INPUT and OUTPUT data as a flexible means of coordinating events in separate stations, eliminating precise bus scheduling, and providing a free bus during critical events. The implementation would require a central clock continuously supplied to all stations. All timing signals, including bit sync, would be derived from the clock signal.

3. DATA MANAGEMENT CONSIDERATIONS

The previous section discussed GN & C System operation to establish data requirements and characteristics. The data bus system must interface with the GN & C System and transfer the data in a manner that satisfies the data requirements. There are two basic functions performed by the data bus system; data management and data transfer. The data management function consists of the interface, format, scheduling, and other aspects involving control of the flow of data. The data transfer function conveys the data format between stations in response to control by data management. The data management function will be considered in this section.

3.1 Data Bus Control

For lack of a specific system structure or operational plan, it will be necessary to consider certain aspects of data management. The flow of data could occur in only three ways; from data processor to a station, from a station to the data processor, or from station to station. The need for two-way data transfer between the data processor and any station is obvious. The need for station to station data transfer is a distinct possibility. Although such data were not identified in Section 2, the LM data in Appendix A lists system to system data between 5 of the 9 GN & C systems. These data could be transferred directly from station to station or routed through the data processor. The first alternative implies that each station be provided with the capability to gain access to the data bus and address the station of interest. The capability could be realized by providing each station with the circuitry required to capture a polling signal in accord with an established priority schedule and that required to generate or store the other station addresses. The resulting interface complexity would exceed that of the other alternative which provides essentially the same capability. Routing all station to station data through the data processor would require only temporary storage within the data processor in addition to the two-way data transfer capability. The station to station data transfer via the data processor requires the minimum redundant hardware. Although the bus time occupancy will be double for these data, the transfer of all station to station data through the data processor will be preferred for its simplicity.

The preceding arguments suggest the data processor serve as a central authority in controlling bus access. Assignment of this authority to the data processor will be logical since it must interface with all stations, maintain cognizance of vehicle configuration and activity, and will be the primary user of the data bus. This policy will simplify the station interface hardware since the station need only respond when interrogated. The data processor will be more complex since it must be programmed with the data rates, the source addresses, and the destination addresses. The complexity will basically be in the software with the necessary redundant hardware confined to the data processor. The resulting arrangement will be consistent with requirements for automatic mode and configuration control.

The scheduling of data transfer is beyond the scope of this report due to the dependence on computer structure, operation, and its programs. It is reasonable to assume that a rigid or repetitive schedule would be unlikely. In fact, the existence of two or more asynchronous computers ensures interleaving of input and output data characteristic of the active program in each computer. Thus, the transfer of various data to or from any station will probably follow a pseudo-random schedule. A time-shared data bus responsive to these needs should attempt to minimize its time occupancy. A low time occupancy reduces the possibility of data backlogs with their attendant scheduling complications and effects on computer operations.

Data bus time occupancy can be reduced by employing a high signalling rate, editing unnecessary data, and providing an efficient address structure. The 1MBPS signalling rate and flag discretes for editing were discussed in Section 2. Address structures will be evaluated in the following paragraph.

3.2 Address Structures

The efficiency of an address structure can be measured in terms of address length compared to data word length. An efficient address structure must provide the desired operational flexibility with a short address length. The use of instruction bits will be neglected here and considered in subsequent paragraphs. Two extreme address structures that provide an upper and lower bound on address efficiency are evident. One extreme would assign a binary address to each data word independent of the station. Such an address structure would have low efficiency and a substantial flexibility. The other extreme would assign only a station address and transfer all station data following the address. This structure would be very efficient for data transfer in large quantities but offers little flexibility. A satisfactory structure must exist within these extremes.

With reference to the data classes of Section 2, possible address structures would include:

1. Address a station (then transfer all station data).
2. Address a station and a class (then transfer that class data).
3. Address a station, a class, and words in that class.
4. Address a station, and words within the station.
5. Address each data word.

The efficiency of these 5 address structures were computed for a hypothetical system that exceeds requirements of the GN & C System. The hypothetical system characteristics were:

Total system words:	$W = 8192$ words
Word length:	$n = 20$ bits/word
Number of stations:	$S = 32$ stations
Data classes:	$C = 4$ classes/station
Data words/station:	$Q = \frac{W}{S} = 256$ words/station

Data words/class

MODE data: Q_M= 2 words/station

INPUT data: Q_I = 15 words/station

OUTPUT data: Q_O = 15 words/station

STATUS data: Q_S = 60 words/station

FAULT data: Q_F = 100 words/station

LOAD data: Q_L = 64 words/station

The effective information rate was computed as the ratio of information bits to information frame time for address lengths commensurate with the hypothetical system data. Instruction bits and pause periods were not included. The results for each address structure are listed in Table 8.

Structure (1) where a station address would be followed by transfer of all MODE, INPUT, OUTPUT, and STATUS data for that station would be competitive with other structures only when more than 75% of these data have been updated. Considering the 20 to 1 spread in average data rates by class, the resultant station updates would occur once every two seconds and would be inadequate.

Structure (2) which transmits a station address and class address followed by transfer of all data in that class has an effective information rate nearly proportional to the percent of updated words in that class. The effective information rate will exceed all others when the updated words are more than 75% of the class total. Since the words are all of the same class, they would be updated at essentially the same time. The high

TABLE VIII.- EFFECTIVE INFORMATION RATE OF VARIOUS ADDRESS STRUCTURES

Address Structure	Effective Information Rate
(1) Station Address	$\frac{V \cdot 20B}{k\lfloor 5+20(Q_M+Q_I+Q_O+Q_S \rfloor T} = \frac{m}{Q+0.25}$ MBPS
(2) Station and Class Address	$\frac{V \cdot 20B}{k\lfloor 5+3+20(Q_i) \rfloor T} = \frac{m}{Q_i+0.4}$ MBPS
(3) Station, Class, and Word Address	$\frac{V \cdot 20B}{k\lfloor 5+3+(7+20)m \rfloor T} = \frac{0.74}{1+\frac{0.30}{m}}$ MBPS
(4) Station and Word Address	$\frac{V \cdot 20B}{k\lfloor 5+(8+20)m \rfloor T} = \frac{0.72}{1+\frac{0.18}{m}}$ MBPS
(5) Word Address	$\frac{V \cdot 20B}{V(13+20)T} = 0.61$ MBPS

NOTES:

1. Address lengths are commensurate with hypothetical problem in text.
2. Information rate was computed for the transfer of 'm' words to each of 'k' stations for a total of 'V' = mk words.
3. Q_F and Q_L were not included since they will be infrequently communicated.
4. B represents 1 bit of information
5. T represents the bit period of 1 microsecond.

effective information rate and elimination of the many word address registers characteristic of the remaining structures are sufficient reasons for preferring this structure.

Structures (3) and (4) have essentially the same effective information rate. It should be noted that the information rate would be significantly reduced for (3), (4), and (5) if coding bits were included. In either event, structure (4) would be preferred to (3) since it would not require the class address registers.

Structure (5) would provide a constant information rate lower than that of (3) and (4). The large quantity of system words and the subsequent address length result in an inefficient structure.

Of the address structures considered, a station address with class address would provide the best efficiency and operational flexibility with minimal address requirements. The transfer of a 'data class' will be compatible with basic GN & C System operation as outlined in Section 2. For instance, all MODE data words would be transferred in a single frame. The INPUT and OUTPUT data of any station will consist of several words. Transfer of either STATUS or FAULT data would consist of several distinct but related words. All LOAD data would be transferred in a single frame. Thus, use of a station and class address conforms to the inherent data flow within the system.

The effective information rate of the recommended address structure can be maintained at a high level by appropriate grouping of data within a class to form subclasses. Each subclass would ideally have the same quantity of data words and would consist of data bearing a common relationship. For example, the hypothetical problem employed the six operational classes of Section 2. Formation of 15 subclasses as shown in Table 9 would ensure a high address efficiency since the number of probable updated words represent a larger percentage of the total subclass data.

The subclasses can be arranged to satisfy the particular requirements of each station. If a station contained only from 6 to 10 INPUT or OUTPUT words, the total data class would inherently be transferred with high efficiency and formation of subclasses would be unnecessary. In this event, the unused subclass address could be used for other data within the station to improve the total data bus efficiency.

The number of class and subclass addresses must satisfy the needs of the most complex system and station. With reference to the estimated system data words in Table 2, and an arbitrary allotment of 4 FAULT subclass addresses and 1 LOAD address, a 4 bit class address would be satisfactory. Since the station address will be 5 bits, perhaps a 5 bit class address would be beneficial in terms of employing a standard 5 bit address length and a standard multiplexer.

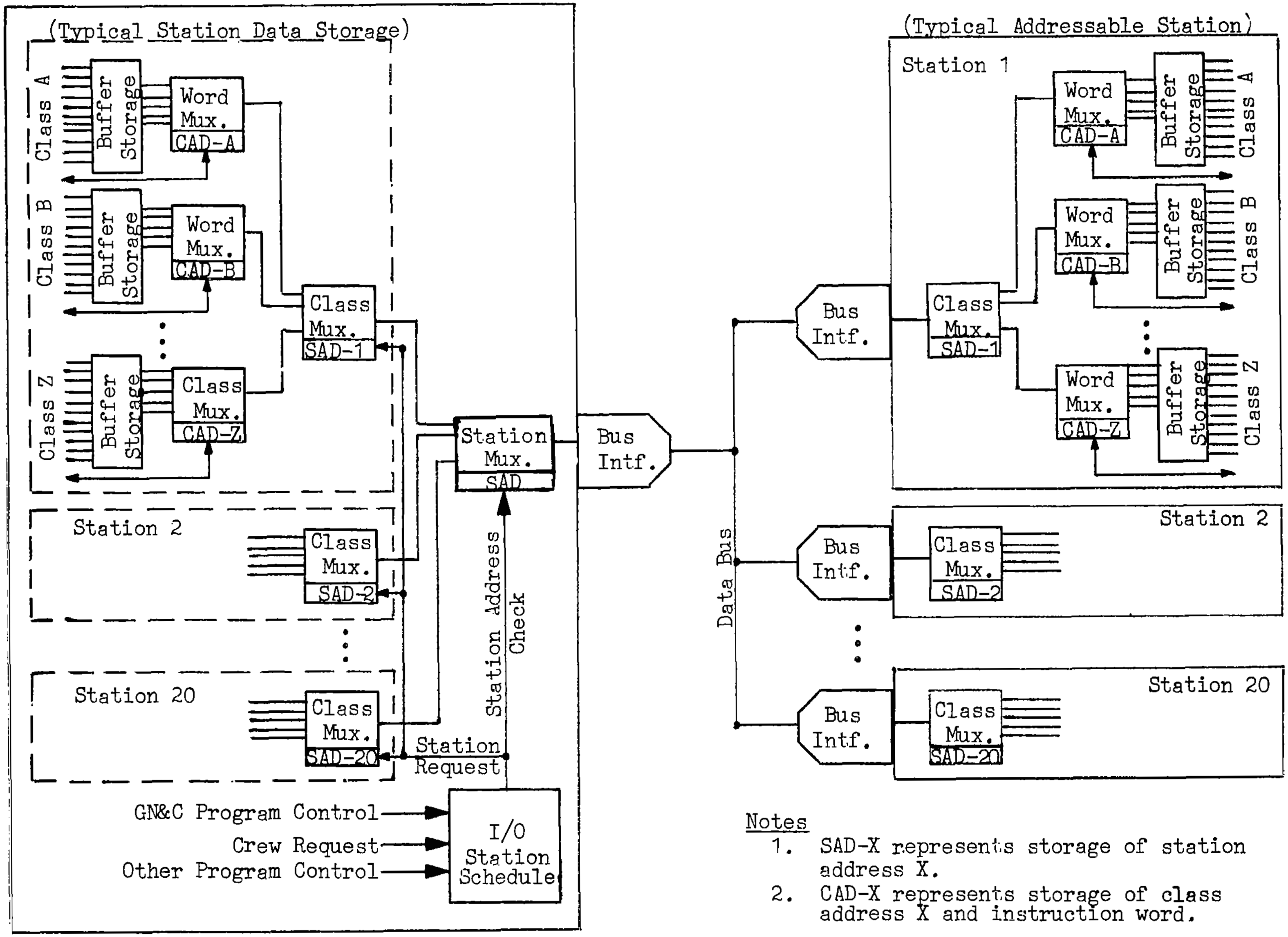
TABLE IX.- EXAMPLE OF DATA SUBCLASSES FOR IMPROVED ADDRESS EFFICIENCY

Hypothetical Problem		Improved Address Efficiency	
Data class	Quantity of words	Data subclass	Quantity of words
MODE	2 words/class	MODE	2 words/class
INPUT	15 words/class	INPUT A	8 words/subclass
		INPUT B	8 words/subclass
OUTPUT	15 words/class	OUTPUT A	8 words/subclass
		OUTPUT B	8 words/subclass
STATUS	60 words/class	STATUS A	12 words/subclass
		STATUS B	12 words/subclass
		STATUS C	12 words/subclass
		STATUS D	12 words/subclass
		STATUS E	12 words/subclass
FAULT	100 words/class	FAULT A	25 words/subclass
		FAULT B	25 words/subclass
		FAULT C	25 words/subclass
		FAULT D	25 words/subclass
LOAD	64 words/class	LOAD	64 words/class

3.3 Data Format

It would be instructive at this point to consolidate previous arguments. These arguments basically emphasize the need for a pseudo-random bus schedule of a variable data format. The data management and multiplexing system functionally illustrated in Figure 7 appears responsive to these needs. The existence of buffer storage for all data to be transferred will be assumed. Within the data processor, the storage could be by assignment in certain cases on a station level or dedicated as indicated by the Figure. The buffer storage would, of course, be dedicated at each station. The data would be assigned to buffer storage arranged in class or subclass data. These data would include the class address word, an instruction word for I/O control or special operations, and all data words corresponding to the particular class and station address. Each word would be parallel transferred in or out of storage by computer control. Data to be transferred to a station would be assigned to storage and its station address inputted to the data bus control. Data to be transferred from a station would be requested by inputting discretes into the instruction word in the proper class buffer storage and its station address into the data bus control.

The data bus control generates an I/O station schedule from requests submitted by GN & C program control, the crew, or other program control such as Command/Display and telemetry. These requests could be executed sequentially in the order received, by priority assignment, or perhaps simply by the number of requests for a particular station.



Notes
1. SAD-X represents storage of station address X.
2. CAD-X represents storage of class address X and instruction word.

Figure 7.- Data management and multiplexing system data processor.

The scheduled station would acquire access to the data bus by a parallel comparison of the station address request with all station addresses in storage. An address detection would enable its class multiplexer and serially clock the station address to the station multiplexer. The station address could be checked serially in the multiplexer as it is transmittted on the bus. Station address errors would inhibit further transmissions and return to data bus control for a repeat operation. The absence of errors would gate the data bus I/O channels to the class multiplexer.

Commencing with the initial station address detection, the class multiplexer would sequentially scan each class for update requests to form its own schedule. These requests could be formed by a logic OR of all word storage load pulses and inputted instructions to determine whether any of the words in the particular class needs to be transferred. If a single word update request exists, the entire data class would be transferred.

After the station address has been clocked out of storage and properly checked at the station multiplexer, the class multiplexer gates the I/O station channels to the first data class to be updated. The class address and instruction word would be serially clocked out through the class and station multiplexers onto the data bus. If the instructions call for data out, the words in buffer storage would be serially clocked out in their assigned sequence. If the instructions call for data in, the class multiplexer inhibits the output channel and enables the input channel. Upon receiving data, the received class address would be compared with the stored address. An error detection would repeat the stored address and instruction words. A proper received address would gate the received data into storage as words in their assigned sequence, neglecting error control procedures for the moment.

The word multiplexer sequences the word storage control signals to inhibit internal read or write pulses during a data bus transfer, and sequentially gates the proper I/O channel to the corresponding buffer storage point. It would be possible to include a serial parity checker within the word multiplexer prior to storage of inputs from the data bus. The check would only identify errors that occurred internal to the data processor. In addition, a word counter would identify underflow and overflow errors or the end of class data. The errors would require a dump of the stored data and would issue a repeat call for data. The end of class data would sequence the class multiplexer to the next class data with an update request.

The process would continue until all class update requests are exhausted. Then, the class multiplexer inhibits the initial station address enable which frees the data bus. The data bus control selects the next scheduled station address and repeats the process.

The operations performed at each station would be similar to those in the data processor. First the received station address would be compared with the stored address. Disagreement would inhibit all data into the station as well as transmissions from the station. Upon detection of the proper station address, the class multiplexer would be enabled. The received class address and instruction words would generate required gating and control signals for transfer of data between the data bus and station buffer storage.

The operational aspects of the data management and multiplexing techniques will provide a flexible response to GN & C System operation. The prominent features include centralized data bus scheduling and access control, simple and efficient address structures, data editing, and extensive use of a few functional circuits throughout the data system. Development of a standard gated shift register, a word multiplexer, a 32 channel multiplexer, and a standard data bus interface would satisfy the functional requirements and provide a substantial economy. The quantity of functional circuit types for 20 addressable stations, each with 16 data classes, and the data processor would be 21 data bus interfaces, 41 multiplexers, 640 word multiplexers, and from 2000 to perhaps 4000 gated shift registers for dedicated buffer storage of 20,000 to 40,000 bits. Half of these quantities would be located in the data processor. Redundancy considerations could perhaps be incorporated in the functional circuit development to avoid the brute force approach of replicating the entire function. Such considerations will have substantial impact on the eventual multiplexing system structure.

The variable data formatting and transfer process would proceed in a timely and smoother manner than presented in the operational discussion. Assume for the moment a 20 bit interrogate word composed of a 5 bit station address, a 5 bit class address and a 10 bit instruction word. In addition, assume a 20 bit control word is transmitted once each data frame. The instruction word and control word will be discussed in subsequent paragraphs. Despite the assumed quantity of interrogate and control bits, the effective information rate of the variable data format remains fairly high. Typical data format characteristics for selected 1 way data transfers are listed in Table 10.

The 1 way transfer of 2 MODE words represents the minimum possible frame time of 80 microseconds and has the least effective information rate. The 2 way transfer of MODE words would be a more likely procedure for effective data processor control. A configuration and status update of 20 stations could be achieved in about 3 milliseconds. The single station data transfer listing represents a complete station update and could also be achieved in about 3 milliseconds. The transfer of MODE data and a single data class would be a reasonable average system data frame. Applying this average to 20 stations reveals an average data bus time occupancy of 6 milliseconds for a complete system update. A system update rate of 10 per second corresponds to 60 KBPS information rate which is reasonably close to the 55 KBPS estimated in Section 2. From these figures, the average data bus time occupancy would be approximately 6%. On the average, 94% of the data bus capacity would be available to service peak demands and repeat transmissions for error control.

TABLE X.- TYPICAL DATA FORMAT CHARACTERISTICS

Data Transfer	Data Format	Number of 20 Bit Word Transmissions	Data Frame Time (microseconds)	Effective Information Rate
2 MODE words	Interrogate word Data words Control word	1 2 1	20 40 20 80	0.50 MBPS
Single data class of 10 words	Interrogate word Data words Control word	1 10 1	20 200 20 240	0.83 MBPS
2 MODE words and a single data class of 10 words	Interrogate word Data words Control word	2 12 1	40 240 20 300	0.80 MBPS
Single station data of 120 words in 16 classes	Interrogate word Data words Control word	16 120 1	320 2400 20 2740	0.88 MBPS

The effective information rates listed in Table 10 vary from 0.50 MBPS to 0.88 MBPS as a function of the quantity of data transferred. It should be noted that the effective information rate increases as the quantity of data increases. This desirable feature results from the address structure employed. The specific limit values result from the quantity of address, instruction, and control bits.

3.4 Special Signals

The data format discussion tacitly assumed the existence of sync signals for frame, word, and bit control. These signals will be generated while the data is being formatted. They must be transferred in some form on the data bus for control at the receiving station. Section 2 justified use of a clock channel to transfer bit sync generated within the data processor. With the data bus control located in the data processor, the frame sync would logically be generated there. A data frame starts when the station address comparator output enables the class multiplexer and ends when the multiplexer inhibits the enable signal. Hence, the class multiplexer enable signal would be a natural frame sync.

The frame sync could be inserted in the clock channel. The minimum frame time of 80 microseconds corresponds to a Nyquist bandwidth of 25KHz. The required clock channel bandwidth will be dependent on the modulation or multiplexing method employed to insert the frame sync. These subjects will be considered in Section 4.

Upon detection of frame sync, each receiving station would be alerted to the start of a data frame and enable the station address for comparison with the received address. The frame signal would be used either to inhibit station transmission or to enable the station class multiplexer depending on the outcome of the address comparison.

The word sync signals will be generated at the data source These signals could be either inserted in the clock channel or uniquely included in the data channel. These possibilities will be considered in Section 4.

An instruction word was frequently mentioned in the discussion of data formatting. This word would contain control information needed for format, multiplexing, and error control of the class data. The instruction word listed in Table 10 consisted of 10 bits assigned as below:

4 bit control instruction

- Output then input data
- Input then output data
- Output data only
- Input data only

6 bit class data word quantity

The instruction word would serve many purposes. By allowing the word to be changed inflight, a number of necessary and useful functions could be realized. The control instruction provides multiplexer control information at the source and destination stations in the modes listed.

The 'output then input' and 'input then output' instructions command a feedback communication mode and designates the source and subsequent location of data comparisons for error control. The data feedback mode will be the nominal operating mode to provide effective error control (see Section 4.3). The technique does not require coding bits whose absence throughout the discussion may have been noticed. It will, however, reduce the effective information rates listed in Table 10 by one-half as a result of the round trip data transfer. The technique requires a special control signal to either acknowledge or accept the data transmissions. This signal will be discussed below and in Section 4.

The 'output only' and 'input only' instructions would result in a single forward transmission only. This capability would be useful for transfer of non-critical data and fault isolation.

The class quantity bits constitute a means of multiplexing control and underflow/overflow checks at the source and destination stations. These bits would represent the quantity of data words in the corresponding data class and would be in fixed memory. The quantity of data words to be transferred will be a useful input for control of the variable data format.

The data feedback technique will require a special control word. The word would be inserted at the end of a data class transfer to signify the end of forward transmissions and command the start of feedback transmissions. The word inserted at the end of feedback transmissions would initiate the source station decision to accept or reject and repeat the transfer. Acceptance would be acknowledged by retransmitting the control word once. Rejection would be signalled by a double transmission of the control word. Possible control word signals are discussed in 4.5.

The data feedback technique and control procedure provide alternate capabilities from that described. Since the criticality of the data class is known at the source station, the forward transfer of non-critical data could be expedited by inserting two consecutive control words to signal acceptance. Another possibility would be to edit the detected errors by their location and signal acceptance dependent on significance of the bit error. These procedures could be used only for non-critical data.

3.5 Summary

Data management considerations and their influence on the data bus were discussed. Arguments were presented that justify assignment of the data bus access control to the data processor. The centralized control of bus access will be consistent with automatic mode and configuration control and provides a basis for computer control of the data bus station schedule. The station hardware will be simplified for this arrangement since it must respond only when interrogated. The interrogation word would include the station address.

The effective information rate of five distinct address structures were listed and discussed. The most desirable address structure consisted of a station address and a data class address followed by transfer of the total data words in the addressed class. The address structure will be compatible with GN & C System operation since several data words will be updated in a single station data frame.

A particular data management and multiplexing system was discussed to indicate the operational capability that could be realized from procedures presented in this report. Circuit details of the system were not included although only four redundant functional blocks would have to be developed. The characteristics of typical data formats were presented for the station and class address structure and assumed error control techniques. A complete configuration and status update of 20 stations could be achieved in about 3 milliseconds. A complete update of a typical station could also be achieved in about 3 milliseconds. A typical station transmission consisting of the transfer of 2 MODE words and a single 10 word data class would require about 300 microseconds. These figures indicate an average data bus time occupancy of about 6% when servicing 20 stations. An average effective information rate of about 0.80 MBPS would be realized for the address structure and assumed quantity of control and special bits. The effective information rate increases as the quantity of transferred data increases.

Most of the data management subjects were given cursory treatment. Consequently, the data management and multiplexing scheme may not constitute the eventual system employed in the SSV. The circuit details and redundancy requirements will certainly influence and perhaps form a constraint on data management. The intent and purpose of the discussion was to demonstrate an operational capability and to indicate supporting signals and data that must be transferred on the data bus.

In addition to GN & C System data and address information, several special signals and data must be transferred on the data bus. These special signals would be required for data control and error control of the data transfer process. These signals were identified as frame, word, and bit syncs, an instruction word, and a control signal. The function and capability of these special signals were discussed. The techniques for multiplexing the data and special signals will be presented in Section 4.

4. DATA COMMUNICATION TECHNIQUES

The primary concern for the GN&C system data bus will be to maintain a reliable transfer of data between stations. The basic measure of data transfer reliability is the word error probability. Word errors will arise from hardware failures and interfering disturbances encountered in the operating environment. Hardware failures can be minimized by employing the simplest communication technique. However, these techniques are the most susceptible to interference. It is apparent that these conflicting factors must be compromised to provide a minimum acceptable error rate. The contents of this section evaluate the performance and suitability of communication techniques in different environments.

4.1 Word Error Rates

The occurrence of single and multiple bit errors during data transfer must be anticipated with incorporation of error detection and correction measures to maintain an acceptable word error rate. The acceptable word error rate depends on the nature and consequences of each specific data. Certainly, all data will be important and the occurrence of data errors undesirable. Nevertheless, critical data must be singled out within the total data volume for special treatment. The objective would be to provide an acceptable word error rate for the total data while employing special techniques for transfer of critical data. These techniques insure that the occurrence of untimely and disastrous events will be highly improbable.

Critical data are related to crew safety, vehicle integrity, and various mission success criteria. Crew safety would be provided for in the vehicle capability and nominal mission plan. Failures that impair vehicle capability and large deviations from the nominal mission would jeopardize both crew safety and vehicle integrity. Hence, critical data would consist of vehicle configuration data, operational and failure data of primary vehicle dynamics, and monitor data of consummables. Relating these to the data classes in this report, all MODE data will be critical while other classes contain critical data only in certain stations.

A value for acceptable word error rates can be obtained from the nominal mission timelines and the signalling rate. Nominal timelines by mission phase were stated in Reference 9 for a 7 day mission and a 30 day mission. These timelines are listed in Table 11 in accord with the critical or non-critical activities of each mission phase. The critical time periods total 1.43 hours or 0.85% of the 7 day mission time and 1.29 hours or 0.18% of the 30 day mission time. These low operational duty cycles indicate critical data errors will be more likely to occur during a non-critical phase.

For a 20 bit word length and a signalling rate of 1 MBPS, an absolute maximum of $5X10^{4}$ words/second can be transferred. Thus, the maximum quantity of data that can be transferred during the total mission critical time will be $2.56X10^{8}$ words for the 7 day mission and $2.34X10^{8}$ words for the 30 day mission. Assuming that 1 word error during a critical mission time period will be allowed in 1000 missions, the acceptable word error probability would be $3.9X10^{-12}$ and $4.3X10^{-12}$ for the respective 7 and 30 day missions.

TABLE XI.- NOMINAL MISSION TIMELINES (Ref. 9)

	7 Day Mission (168 Hours)				30 Day Mission (720 Hours)			
	Critical Time	Non-Critical Time	Phase Time	% of Mission Time	Critical Time	Non-Critical Time	Phase Time	% of Mission Time
Prelaunch		1.00	1.00	0.6%		1.00	1.00	0.14%
Launch			.60	0.36%			.60	0.09%
Burn time	.15				.15			
Coast to insertion		.45				.45		
Orbit Determination		.80	.80	0.48%		1.70	1.70	0.24%
Coast		.80	.80	0.48%		605.00	605.00	84.30%
Rendezvous			4.12	2.45%			8.24	1.15%
Burn time	.12				.24			
Coast		4.00				8.00		
Stationkeep and Docking			2.34	1.41%			102.08	14.10%
Stationkeep		1.00			.06	100.00		
Docking	.33					-		
Separation preparation		1.00				2.00		
Separation burn	.01				.02			
Inactive			157.00	93.45%	-	-	-	-
Unloading		4.00			-	-	-	-
Docked stay		153.00			-	-	-	-
Entry and Transition			1.04	0.62%			1.04	0.14%
Deorbit burn	.09				.09			
Deorbit coast		.56				.56		
Entry Orientation	.10				.10			
Entry	.28				.28			
Subsonic transition	.01				.01			
Cruise (Powered Flight)	.17		.17	0.1%	.17		.17	0.02%
Landing	.17		.17	0.1%	.17		.17	0.02%
Total Hours	1.43	166.61	168.04	-	1.29	718.71	720.00	-
% of Mission Time	0.85%	99.15%	-	-	0.18%	99.82%	-	-
% of Active Mission Time	12.9%	87.1%	-	-	0.18%	99.82%	-	-

Applying these probabilities to the maximum words per mission (1.98×10^9 words for the active 11 hours of the 7 day mission and 1.296×10^{11} words for the 30 day mission), an average of 1 word error during 100-7 day missions and 1 word error during 2-30 day missions would be expected.

The word error probability of 10^{-12} was obtained from very conservative assumptions that represent a worst case. Previous considerations indicated the data bus would operate at about 6% of capacity which reduces the expected word error rate by a factor of sixteen. In addition, word errors were tacitly assumed to occur equally likely among all data. On this basis, critical errors would occur in proportion to their ratio of the total data. By incorporating these two factors, a maximum word error rate of 10^{-10} would be allowed to satisfy the stated error criteria and the expected word errors per mission. The 10^{-10} value represents a lower bound on communication channel performance.

4.2 Channel Error Probability

A word error probability of 10^{-10} for a 20 bit word could be justified by the preceding analysis. The word error probability (P_W) can be related to the channel bit error probability (P_e) by assuming each bit to be an independent Bernoulli trial. With this assumption, the probability of exactly i bit errors in a word can be computed from the Binomial distribution

$$P(\text{i bit errors per word}) = \binom{n}{i} P_e^{\,i} (1-P_e)^{n-i}$$

where n is the word length

and $\binom{n}{i} = \frac{n!}{i!(n-i)!}$ are Binomial coefficients.

In general, a word error results from j or more bit errors, and the word error probability will be

$$P_w = \sum_{i=j}^{n} \binom{n}{i} P_e^{\,i} (1-P_e)^{n-i}.$$

Thus, there are basically two approaches to obtain an acceptable word error rate:

1. minimize the word error subset size
2. minimize the channel error probability.

The first approach can be realized by coding the data in a unique manner that allows detection and correction of certain error patterns. Since this approach requires encoding and decoding equipment in addition to the basic communication equipment, it would be prudent to first determine the performance capability of the basic equipments to establish the need for coding.

For uncoded data, a word error results when at least one bit error occurs. Hence, the uncoded word error probability will be

$$P_w = \sum_{i=1}^{n} \binom{n}{i} P_e^{\,i} (1-P_e)^{n-i}$$

$$= 1-\binom{n}{o} P_e^{\,o} (1-P_e)^{n}$$

$$= 1-\left\lfloor 1-nP_e+\frac{n(n-1)}{2} (P_e)^2-. . . \right\rfloor$$

or

$$P_w \approx nP_e \quad \text{for} \quad nP_e \ll 1.$$

Hence, the word error probability will be approximately the product of the word length and the channel bit error probability. The expected value or average bit errors per word is exactly equal to this product. The discussion in Section 2 indicated 20 information bits per word would be adequate for the information to be transferred. Thus, the uncoded word error rate would require a channel bit error rate of less than $5X10^{-12}$.

The channel bit error rate will be dependent on the energy per bit, the signalling and detection technique, and the channel characteristics. Two basic models of channel characteristics that apply to the SSV data bus are:

- white, Gaussian channel (WGC)
- noise burst channel (NBC).

4.2.1 White Gaussian Channel

The WGC has been extensively analyzed and reported in the literature. The channel error probabilities for amplitude, frequency and phase shift keying with coherent or non-coherent detection are listed on Table 12 and presented as Figure 8. At a given E/No, P_e differs by several orders of magnitude between the different techniques. However, a particualr P_e can be obtained with all of the techniques by simply increasing the signal power 3 db or less when operating above about 10 db. The bit error probabilities for large E/No decrease exponentially with E/No as listed in Table 12. At E/No of 16db, P_e varies from about 10^{-7} to 10^{-15}. An

TABLE XII.- BIT ERROR PROBABILITY FOR A WHITE, GAUSSIAN CHANNEL

Signal and Detection Technique	P_e	P_e for large E/No
Amplitude Shift Keying (ASK)		
o Non-coherent detection (3)	$\approx \frac{1}{2}\left[\frac{1}{2}\,\mathrm{erfc}\left(\sqrt{E/2No}\right)+\exp(-E/2No)\right]$	$\frac{\exp(-E/2No)}{2}$
o Coherent detection	$\frac{\mathrm{erfc}\left(\sqrt{E/2No}\right)}{2}$	$\frac{\exp(-E/2No)}{2\sqrt{\pi E/2No}}$
Frequency Shift Keying		
o Non-coherent detection	$\frac{\exp(-E/2No)}{2}$	$\frac{\exp(-E/2No)}{2}$
o Coherent detection	$\frac{\mathrm{erfc}\left(\sqrt{E/2No}\right)}{2}$	$\frac{\exp(-E/2No)}{2\sqrt{\pi E/2No}}$
Phase Shift Keying (PSK)		
o Differentially coherent (DPSK)	$\frac{\exp(-E/No)}{2}$	$\frac{\exp(-E/No)}{2}$
o Bi-phase (BPSK)	$\frac{\mathrm{erfc}\sqrt{E/No}}{2}$	$\frac{\exp(-E/No)}{2\sqrt{\pi E/No}}$

Notes:
1. E is the average signal energy per bit.
2. No is the noise power per unit bandwidth.
3. Assumes an optimum threshold level at $\sqrt{2+E/2No}$

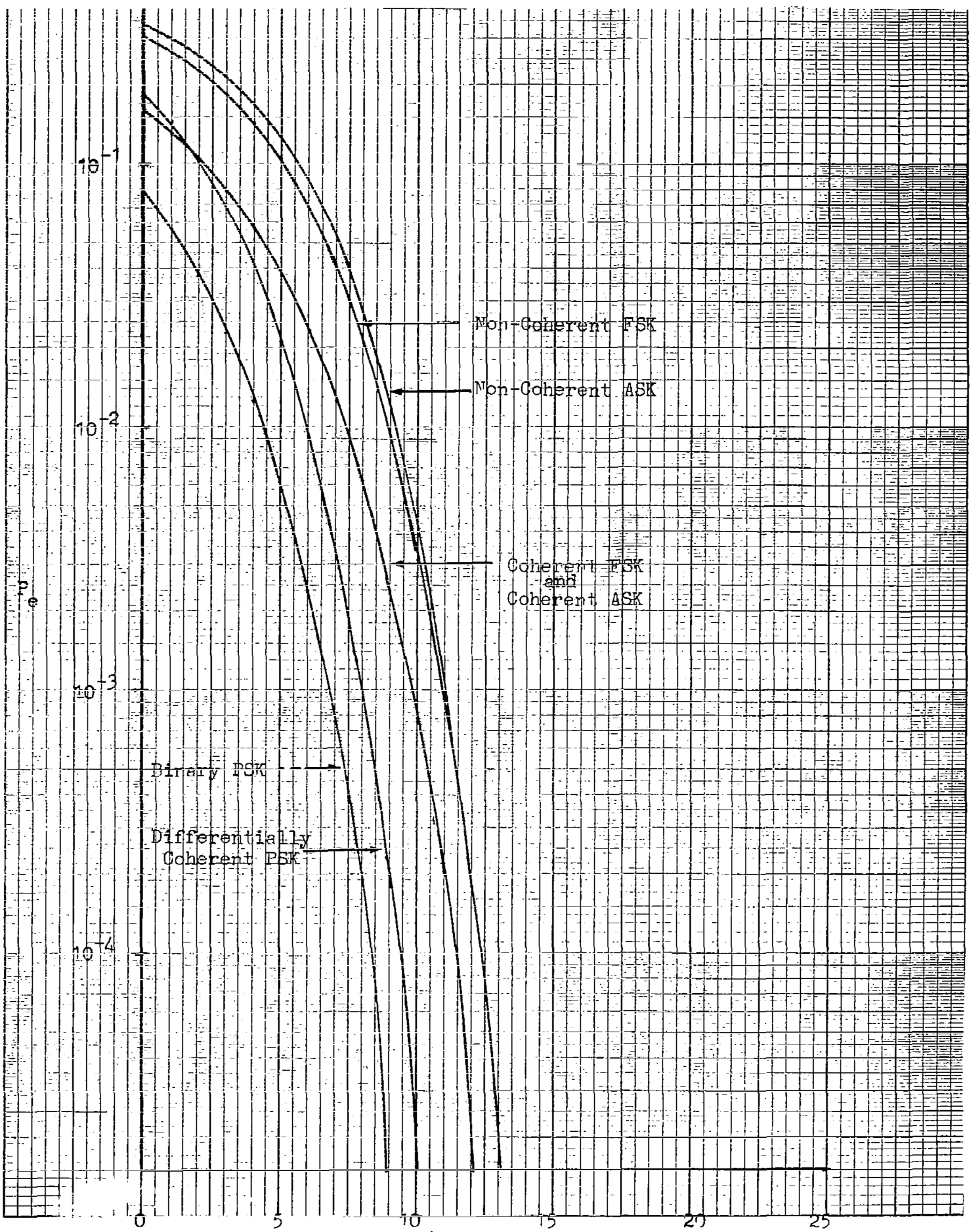


Figure 8.- Bit error probabilities for white Gaussian channel.

expectation of E/No greater than 20 db on the data bus would be reasonable. At this level, the word error rate would be realized without coding in a WGC.

4.2.2 Noise Burst Channel

Unfortunately, the white, Gaussian channel model is unreliable at such a high E/No as evidenced by reported measurements of hardwired digital data communication systems in the literature. The measurements reveal large energy bursts will occur far more frequently than expected in a WGC. The Bell System Technical Journal contains a wealth of information on burst error statistics of telephone toll lines (Ref. 10). Although these burst statistics do not apply directly to the data bus, it would be reasonable to assume that burst errors will occur and limit data bus performance. These noise bursts would be electro-magnetically coupled onto the data bus line from radar pulses, keyed data transmissions, electric actuators, and electrical power transients. The electro-magnetic (EM) susceptibility of the data bus will certainly be controllable by EM design considerations. Nevertheless, a shield break or a faulty ground, for example, could result in a severe EM environment that seriously degrades or limits data bus performance. For these reasons and the fact that adequate signal power overcomes limitations of the WGC, data bus performance on a noise burst channel (NBC) will be important.

The primary characteristics of a NBC are statistics of the burst interval, the burst duration, the burst energy, and the burst energy spectrum. These data do not exist and will not be available for the SSV EM environment for some time. Instead of speculating on these data, it would be desirable to relate burst parameters to channel error rate from which trends can be extrapolated. The desired relations were published by Engel and will be summarized below (Ref. 11).

Engel computed the conditional error rate for the average number of bit errors, given that a noise burst has occurred, for several signalling techniques subject to an average power constraint. The computations were performed for a burst energy spectrum determined by a band-limited channel and with burst amplitude described by the probability density function,

$$p(K>X) = \left(\frac{K_0}{X}\right)^{2\alpha}, \quad X \geq K_0$$

where

K is the burst amplitude

K_0 is a reference amplitude chosen such that only larger burst amplitudes cause errors

α is a parameter of the channel burst characteristic.

These burst amplitude statistics correspond reasonably well to measurement data of telephone lines where the parameter α was found to be constant for any particular channel and with a variable magnitude of 1 to 2.5 from channel to channel. A large α corresponds to a channel with a small percentage of high amplitude bursts which results in a low conditional error rate. A small α corresponds to a channel with a large percentage of high amplitude bursts which results in a high conditional error rate. The value, α=1, represents an infinite average energy per burst which forms a lower bound on α and an upper bound on the conditional error rate. The distribution of noise burst amplitudes is plotted in Figure 9 for α=1, 2, 3.

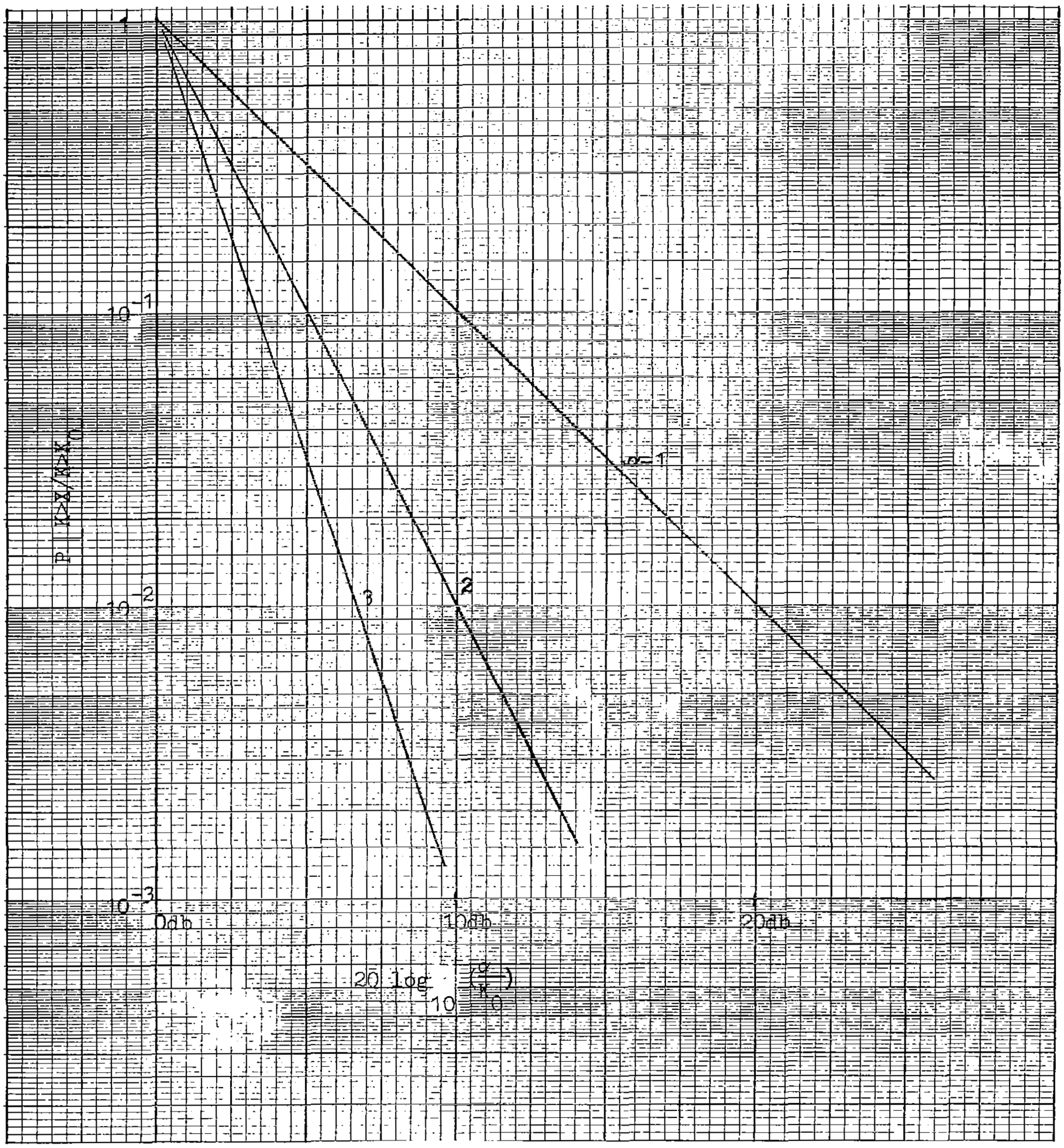


Figure 9.- Distribution of noise burst amplitudes.

For a normalized burst envelope, the burst energy equals the burst amplitude squared, and the minimum burst energy reference will be

$$\varepsilon_0 = K_0^2.$$

Measured burst data reveals the average interval between bursts to be much greater than the burst duration so that overlapping bursts would be improbable. In addition, these data indicate the burst intervals to be approximately Poisson distributed with parameter

$$\beta = \frac{\text{average number of bursts with energy} > \varepsilon_0}{\text{unit time}}$$

With these observations, the channel error probability will be a function of α, β, ε_0, and E, the average signal energy per bit. Since P_e is the average number of bit errors per bit transmitted, the average number of bit errors per burst is the conditional error rate given by,

$$\overline{N} = \frac{P_e}{\beta T}$$

where T is the bit period.

Engels proceeded to calculate $\overline{N}$ of several signalling techniques for:

1. A raised cosine data pulse spectrum
2. A constant noise burst spectrum in the band of interest
3. A receiver filter that minimized $\overline{N}$ for $\alpha=1$.

and

4. A linear filter phase characteristic.

The results are listed in Table 13 and plotted in Figures 10, 11, and 12.

TABLE XIII.- CONDITIONAL BIT ERROR PROBABILITY FOR A NOISE BURST CHANNEL (Ref. 11)

	$\overline{N} = \frac{P_e}{\beta T}$		
Signal and Detection Technique	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$
Amplitude Shift Keying			
o Non-Coherent Detection	$0.455(\frac{\epsilon_0}{E})$	$0.456(\frac{\epsilon_0}{E})^2$	$0.586(\frac{\epsilon_0}{E})^3$
Frequency Shift Keying			
o Coherent Detection	$0.402(\frac{\epsilon_0}{E})$	$0.392(\frac{\epsilon_0}{E})^2$	$0.480(\frac{\epsilon_0}{E})^3$
Phase Shift Keying			
o Differentially Coherent	$0.236(\frac{\epsilon_0}{E})$	$0.109(\frac{\epsilon_0}{E})^2$	$0.0625(\frac{\epsilon_0}{E})^3$
o Bi-phase	$0.124(\frac{\epsilon_0}{E})$	$0.0545(\frac{\epsilon_0}{E})^2$	$0.0302(\frac{\epsilon_0}{E})^3$

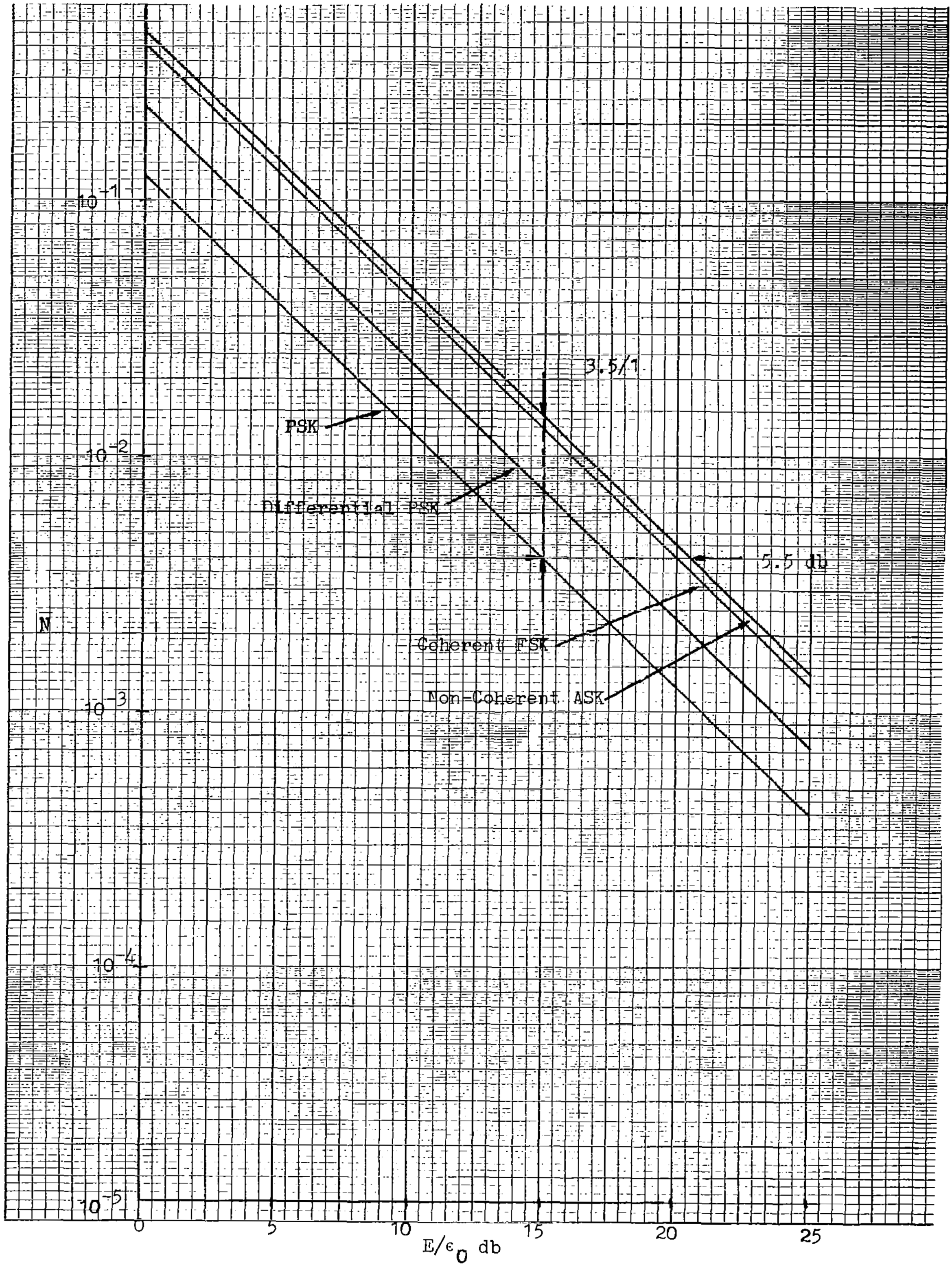


Figure 10.- Conditional bit error probability of a noise burst channel for $\alpha = 1$.

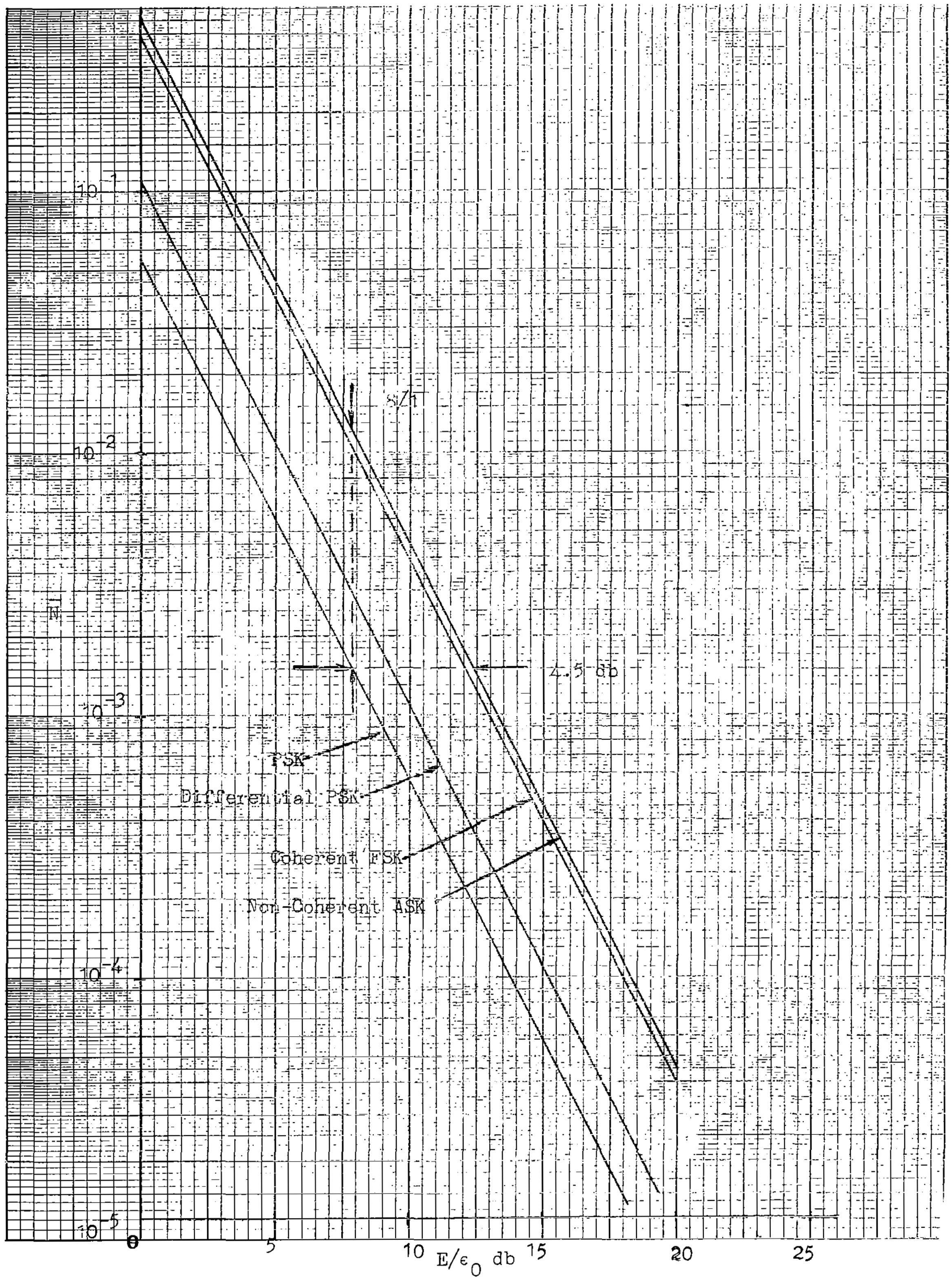


Figure 11.- Conditional bit error probability of a noise burst channel for α = 2.

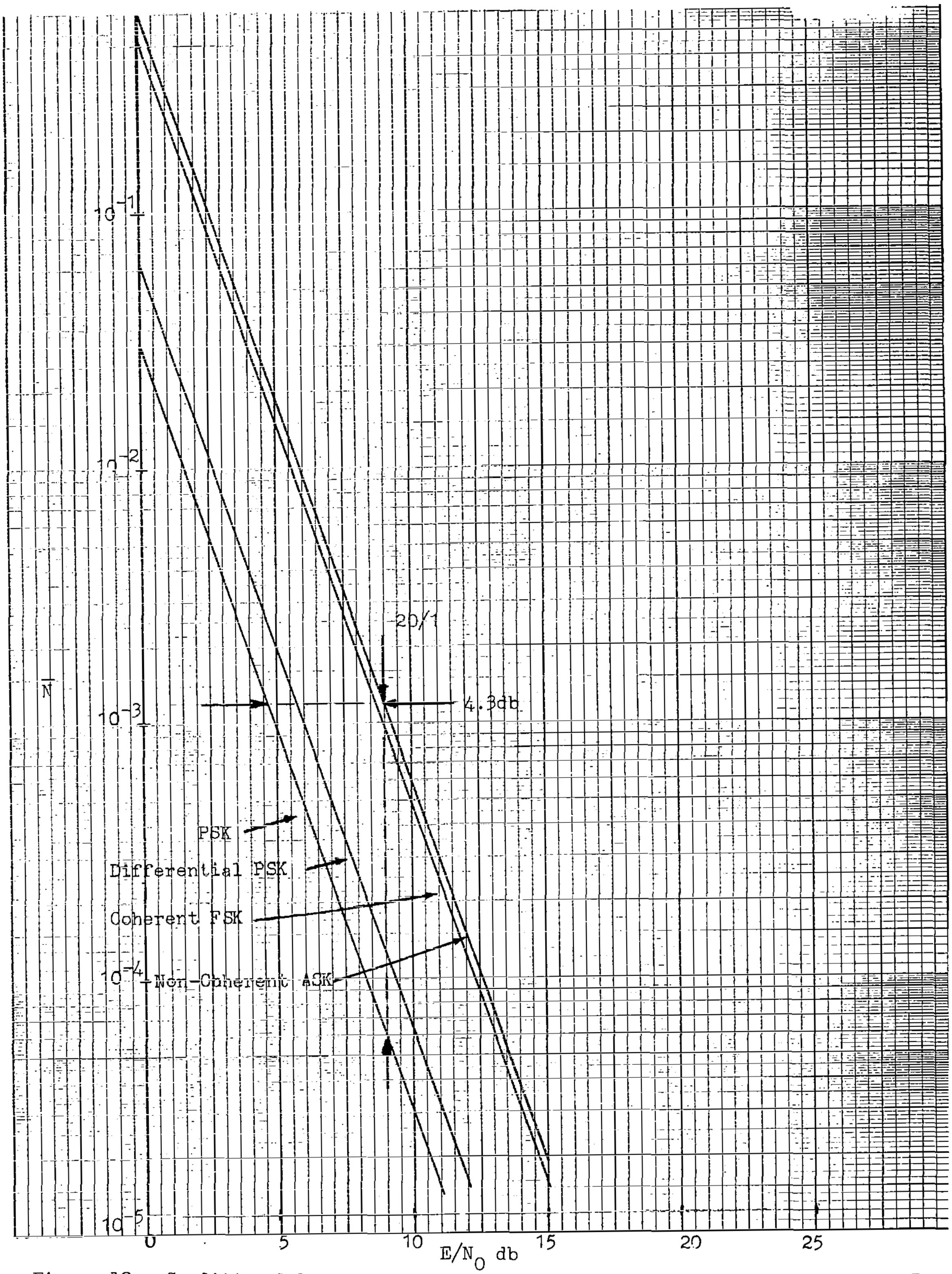


Figure 12.- Conditional bit error probability of a noise burst channel for $\alpha = 3$.

Comparison of these results with the WGC in Figure 8 for $No \approx \epsilon_0$ indicates the NBC errors will dominate at high E/No (or E/ϵ_0) as initially stated. The figures also demonstrate the change in $\bar{N}$ for different signalling and detection techniques will not be as significant as the difference in P_e of the WGC. A reduction of $\bar{N}$ by a factor of 3.5, 8, and 20 for channels with α = 1, 2, and 3, respectively, represent the improvement obtained form the choice of signalling and detection techniques for an average power constraint. Equivalent performance between the techniques can be realized by increasing the average signal power by 5.5 db, 4.5 db, and 4.3 db for the respective channels. The average power performance rating of the different signalling techniques on a NBC are identical to their rating on a WGC. The channel error rate will be a minimum for bi-phase PSK and a maximum for non-coherent detection of ASK.

The significance of the preceding remarks centers around the fact that the channel error rate of the most complex signalling technique can be realized with the simplest technique by increasing the signal power less than 6 db. The suitability of increasing signal power will be constrained by the maximum power output of available devices and dependent on the burst parameters, α, β, and ϵ_0. The resultant channel error rate of bi-phase PSK and non-coherent ASK are shown in Figure 13 for the upper bound of α=1 and selected values of β. Although an E/ϵ_0 of 30 db would be considered a high quality channel, the channel error rate would range from 10^{-12} to 10^{-8} as the channel burst rate degraded from .01 to 100. Thus, it would be possible to obtain the desired word error rate without coding only if the channel burst rate was on the order of .001. The low value seems unlikely for the SSV EM environment. In absence of a specific

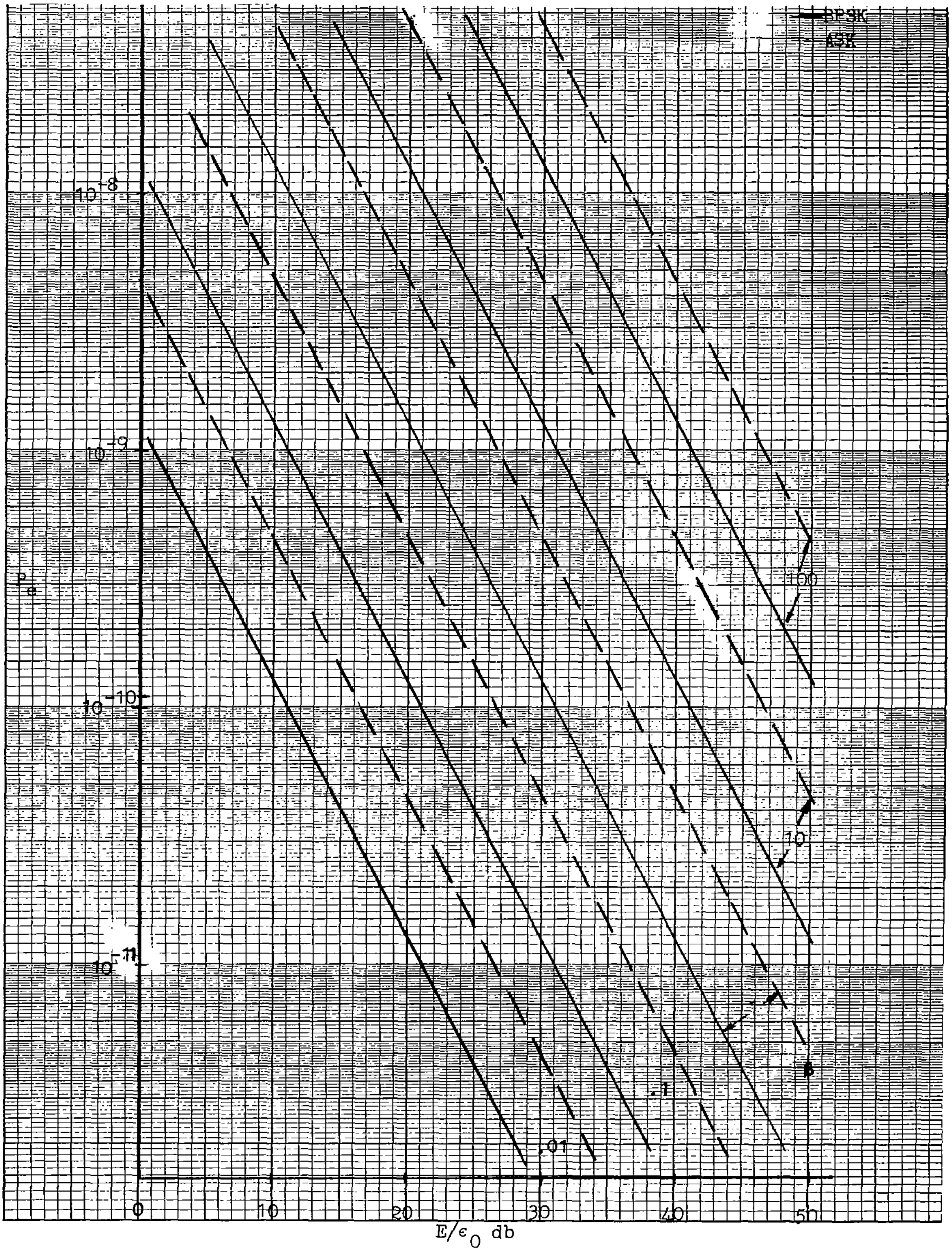


Figure 13.- Bit error probability of a noise burst channel for $\alpha = 1$ and selected values of β.

channel description, it will be necessary to anticipate burst errors and employ some form of error control.

4.3 Error Control Techniques

The probability of a word error was given as

$$P_w = \sum_{i=j}^{n} \binom{n}{i} P_e^{\,i} (1-P_e)^{n-i}$$

with the assumption that channel bit errors were independent. The assumption is questionable on a burst channel where several consecutive bit errors will occur due to a single noise burst. Mathematical models of burst channels have been developed that correlate well with measured data (Ref. 12, 13, 14). These models will not be discussed since certain model parameters are empirically obtained from measured data that does not exist for the SSV. The discussion here will include several error control techniques, their attributes, and their suitability for use on the GN&C data bus.

The specific techniques to be discussed are:

1. Majority vote of independent channels
2. Majority vote of redundant transmissions
3. Error detection coding
4. Error correction coding
5. Error detection coding/retransmission
6. Data feedback

The motivation for employing error control is to improve the word error rate better than that obtainable from the basic channel error rate. A rational criteria for selecting a particular technique would be to obtain the highest reliable information rate that involves the least equipment complexity. The effectiveness of each technique can be determined on a probabilistic basis as reported in Appendix B. The basis recognizes the fact that only three possibilities exist for received and processed data:

- correct information is outputted
- incorrect information is outputted
- information is rejected.

Of these possibilities, only the correct information output is desired. Hence, its probability should be maximized and the probability of outputting incorrect information should be minimized. The possibility of rejecting information requires some criteria of acceptance which is obtained either by processing the received data with a known coded structure or by comparison of the recieved data with the transmitted data. In general, these techniques function to increase the probability of rejecting instead of outputting incorrect data. Since the data must be outputted, rejecting data is unacceptable. However, rejected data would be cause for a retransmission with hopes of receiving it in an acceptable form. The repeat transmissions represent an exchange of bus capacity for reliable information. The effectiveness of each error control technique is discussed below and summarized in Tables 14 and 15. A functional diagram of these techniques is presented in Figure 14.

4.3.1 Majority Vote of Independent Channels

The requirement for redundant channels can be utilized to improve the word error rate if channel errors occur independently. A degree of independence could be obtained by employing different

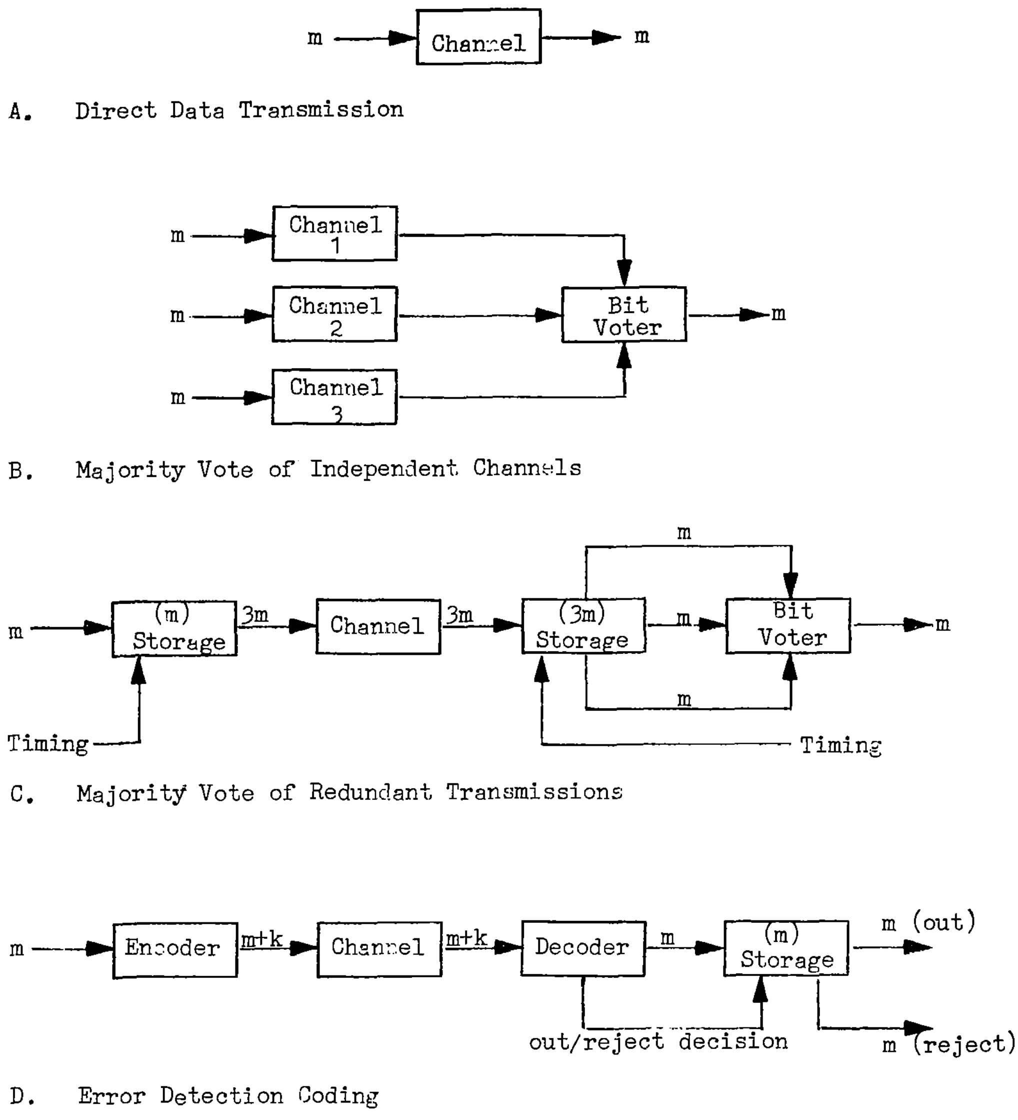
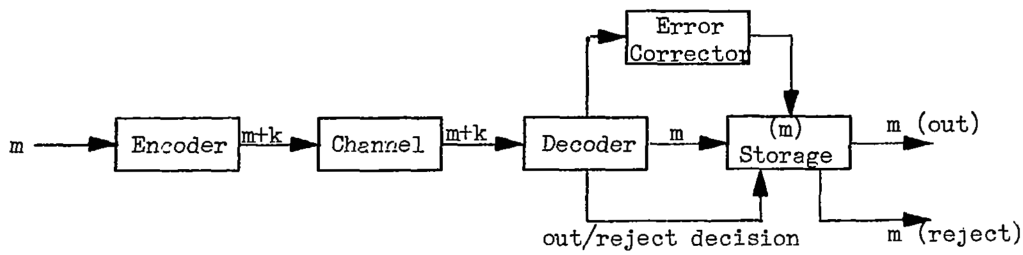
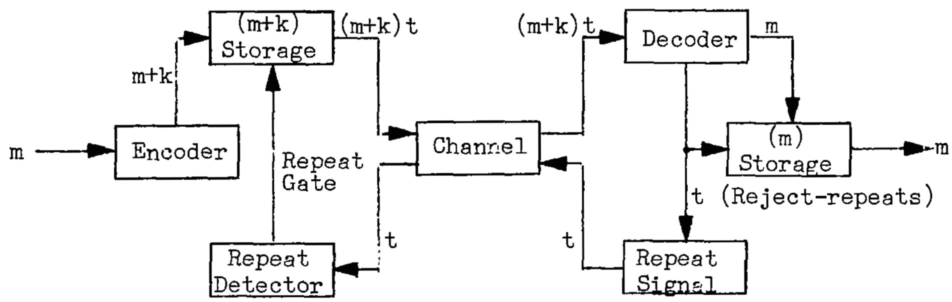


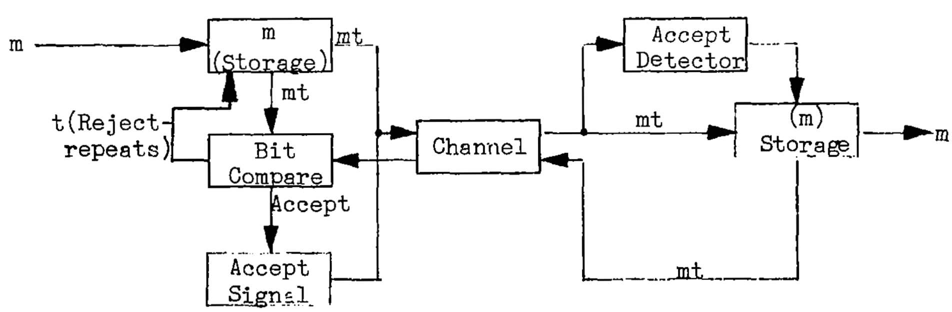
Figure 14.- Functional diagram of error control techniques.



E. Error Correction Coding



F. Error Detection Coding/Retransmission



G. Data Feedback

Figure 14.- Functional diagram of error control techniques (concluded).

routes for each redundant line. The uncoded information would be passed thru each channel with a bit by bit majority rule prior to output. For three channels, the effective output bit error rate will be

$$P_b = \sum_{i=2}^{3} \binom{3}{i} P_e^{\,i} \, (1-P_e)^{3-i} \approx 3P_e^{\,2}.$$

Since there can be no indecision for odd channel voting, data cannot be rejected. Hence, the technique functions to improve the effective output bit error rate which increases the probability of outputting correct information. The source rate and signalling rate would be identical since there are no transmission delays. The technique has minimal hardware requirements consisting of voting logic at receiving stations.

The usefulness of this technique is totally dependent on channel independence. Obtaining independence through cable routing alone would be of limited success since each line must enter all electrically active vehicle stations and couple into each data bus interface. In addition, the technique is extremely sensitive to channel faults.

4.3.2 Majority Vote of Redundant Transmissions

A more predictable method of achieving independent bit errors would be to redundantly transmit the data serially into storage at the receiving station for bit by bit majority voting of all received data. The channel independence would result from the time diversity transmissions. Although the output probabilities for three transmissions would be identical to those of 4.3.1, they could be realized with more confidence. However, the source rate would have to be buffered since the throughput rate would be only one-third of the signalling rate. The technique requires buffer storage at the source and receiver station in addition to bit voting logic at receiver stations.

The usefulness of this technique is limited by the substantial limitation in throughput rate. Although other techniques utilize data bus capacity more efficiently, this technique would require little hardware.

4.3.3 Error Detection Coding

By transmitting encoded data, the occurrence of certain error patterns can be detected with subsequent rejection of the data. The technique functions to lower the probability of outputting incorrect information by rejecting it instead. No improvement in correct output information is realized. The error detection capability is a function of the number of coding or check bits transmitted with the data. To provide sufficient error detectability and maintain a high throughput rate, blocks of data must be encoded. The technique requires an encoder at the source station and a decoder with block storage at the receiver station.

The usefulness of the technique is limited by the rejection of data, the lack of improvement in outputting correct data, and the error detection capability of the code.

4.3.4 Error Correction Coding

By properly encoding data, received errors can be detected and corrected. The technique functions to lower the probability of outputting incorrect data by correcting certain error patterns while detecting and rejecting other error patterns. Error correction codes require substantially more coding bits than needed for detection which leads to a compromise between error correction capability and throughput rate. The technique requires an encoder at the source station (comparable to that needed for error detection encoding) and a relatively complex decoder with computation capability in addition to block storage at receiver stations. The usefulness of the technique is limited by the high redundancy always transmitted to correct errors should they occur. In addition, the correction capability is dependent on the occurrence of certain error patterns which requires reliable information about channel characteristics. A channel that degrades beyond the code correction limitations generally results in decoding errors that appear as additional incorrect output information.

4.3.5 Error Detection Coding/Retransmission

This technique increases the probability of outputting correct information by employing an error detection code with correction by retransmission. The technique offers the lower redundancy of an error detection code with greater capability for correction than obtainable from error correction coding. The data is encoded, assigned to buffer storage and transmitted from the source station to the receiver station. The received data is decoded while searching for error patterns. If no error patterns are detected, the information is outputted. By employing a block code, reasonable assurance can be provided that the outputted data does not contain errors and therefore is correct. In the event of error detection, the data would be rejected and a repeat transmission request issued to the source. The source would call the encoded data from buffer storage and iterate the transmission cycle.

In addition to the encoder and decoder, hardware for the following functions would be needed:

1. Special signal to acknowledge correct reception
2. Special signal to request a repeat transmission
3. Buffer storage at both stations
4. A request counter that alarms a bus tie-up

The usefulness of the technique is limited by the efficiency of the error detection code, the reduction of throughput rate on a poor channel, and the special hardware needed for the repeat capability.

4.3.6 Data Feedback

The most positive technique of outputting correct information employs data feedback. The uncoded source data is placed in buffer storage and transmitted to the receiver. The receiver station places the data in buffer storage and feeds the data back to the source. The feedback data is compared with the stored data to detect errors. In the absence of errors, the source signals the receiver to accept its stored data. In the event of an error detection, the transmission cycle is iterated. The technique does not require encoders and decoders and can be implemented with the following:

1. Buffer storage at both stations
2. A bit comparator at the source station

3. An "Acknowledge/Accept" signal

4. A retransmit counter that alarms a bus tie-up.

The usefulness of the technique is limited by the feedback transmission of the data, which lowers the throughput rate on a poor channel.

4.3.7 Evaluation of Error Control Techniques

The effectiveness and attributes of the error control techniques are listed in Tables 14 and 15 for comparison. An evaluation of these techniques for use on the GN&C system data bus results in the order of preference entered in Table 15 and justified below.

Error detection coding alone would not be acceptable due to the rejection and subsequent loss of data.

Although error correction coding provides some improvement in outputting correct information and reduces the probability of rejecting data, the complex decoding and dependence on channel characteristics eliminates this technique.

A majority vote of independent channels would provide acceptable performance in normal operation. The performance could not be maintained in a fault condition that causes the loss of a redundant channel or couples interference into a majority of channels. The poor fault tolerance of this technique renders it unacceptable since an alternate technique would be required.

TABLE 14.- EFFECTIVENESS OF ERROR CONTROL TECHNIQUES ON A GAUSSIAN CHANNEL*

	No error control	Majority vote of 3 independent channels	Majority vote of 3 redundant transmissions	Error detection coding	Error correction coding	Error detection coding and retransmission	Data feedback
Channel Error Rate	P_e	$\approx 3P_e^2$	$\approx 3P_e^2$	P_e	P_e	P_e	P_e
Correct Output Rate (P_C)	$1-mP_e$	$1-3mP_e^2$	$1-3mP_e^2$	$1-nP_e$	$1-nP_e \lfloor 1-P_{c/d} \cdot P_d \rfloor$	$\frac{1-nP_e}{1-nP_e \cdot P_d} \lfloor 1-P_R \rfloor$	$\frac{(1-2mP_e) \lfloor 1-P_R \rfloor}{1-2mP_e(1-2^{-2m})}$
Incorrect Output Rate (P_I)	mP_e	$3mP_e^2$	$3mP_e^2$	$nP_e \cdot \lfloor 1-P_d \rfloor$	$nP_e \lfloor 1-P_d \rfloor$	$\frac{nP_e(1-P_d)}{1-nP_eP_d} \lfloor 1-P_R \rfloor$	$\frac{2mP_e 2^{-2m} \lfloor 1-P_R \rfloor}{1-2mP_e(1-2^{-2m})}$
Reject Rate (P_R)	NONE	NONE	NONE	$nP_e \cdot P_d$	$nP_e \lfloor 1-P_{c/d} \rfloor \cdot P_d$	REPEATS	REPEATS
Repeat Rate for t Transmissions (P_R)	NONE	NONE	NONE	NONE	NONE	$(nP_eP_d)^t$	$\{2mP_e(1-2^{-2m})\}^t$
Reliable Information Rate (F)	$\frac{(1-mP_e)}{T}$	$\frac{(1-3mP_e^2)}{T}$	$\frac{(1-3MP_e^2)}{3T}$	$\frac{1-nP_e}{n/m \cdot T}$	$\frac{1-nP_e \lfloor 1-P_{c/d} \cdot P_d \rfloor}{n/m \cdot T}$	$\frac{(1-nP_e) \lfloor 1-(nP_eP_d)^t \rfloor}{\cdot t\, n/m \cdot T(1-nP_eP_d)}$	$\frac{(1-2mP_e) \lfloor 1-P_R \rfloor}{2tT\{1-2mP_e(1-2^{-2m})\}}$

*See Appendix B for derivations and definitions.

TABLE 15.- ATTRIBUTES OF ERROR CONTROL TECHNIQUES

	Majority vote of independent channels	Majority vote of redundant transmissions	Error detection coding	Error correction coding	Error detection coding and retransmission	Data feedback
Increases Correct Output	YES	YES	NO	YES	YES	YES
Rejects Data	NO	NO	YES	YES	NO (Repeats transmission)	NO (Repeats transmission)
Throughput Rate	HIGH	LOW	HIGH	MODERATE	Normally High but channel dependent	Normally Moderate but channel dependent
Transmission Delay	NONE	FIXED	NONE	FIXED	VARIABLE	VARIABLE
Channel Type	Multiple Simplex	Simplex	Simplex	Simplex	Duplex	Duplex
Dependence on Channel Characteristics	HIGH	MODERATE	MODERATE	HIGH	ADAPTIVE	ADAPTIVE
Complexity	LOW	LOW	MODERATE	HIGH	MODERATE	MODERATE
Limitations	Channels Must Be Independent	Low Throughput Rate	Rejects Data	High Redundancy Code and Complex Decoder	Requires Auxiliary Hardware	Moderate Throughput Rate
Order of Preference	4	3	6	5	2	1

A majority vote of redundant transmissions is an attractive candidate due to its hardware simplicity. The technique offers an exchange of bus capacity for data reliability on a single operational line. The number of redundant transmissions required would be dependent on the channel error rate. An outputted word error rate of 10^{-10} for a 20 bit block would require 3 redundant transmissions for channel error rates up to 10^{-6} and 5 redundant transmissions for channel error rates up to 10^{-4}. The attendant reduction in throughput rate of 1/3 and 1/5, respectively, creates cause for concern. The simplest implementation would employ three redundant transmissions and accept the subsequent performance degradation with channel error rate. A definite disadvantage of this technique is the low throughput rate that would exist on a high quality channel. A more favorable technique would adaptively exchange bus capacity for data reliability as a function of channel quality or the occurrence of errors. The adaptive attributes of error detection coding/retransmission and data feedback inherently offer this flexibility.

Error detection coding and retransmission for correction provides the means for adapting the throughput rate for short or long term channel degradation. The use of an effective error detection code would ensure a high probability of outputting correct information while the number of retransmissions required would be dependent on channel quality and block length. On a high quality channel, retransmissions would infrequently occur with the throughput rate limited approximately by the code redundancy. The throughput rate in this instance would be a factor of 2 to 3 faster than obtained with redundant transmissions and from 1 to 2 times faster than data feedback. Although the high quality channel represents nominal operation, a low quality channel represents a fault condition that must be anticipated.

The primary difference between redundant transmissions and repeat transmissions is a question of priorities. Redundant transmissions maintain a constant throughput rate as the channel quality deteriorates by accepting a lower probability of outputting correct information. In contrast, techniques which employ repeat transmissions maintains the probability of outputting correct information by lowering the throughput rate as channel quality deteriorates. Considering the consequences of a lower data rate as opposed to a higher probability of data error, it becomes evident that repeat transmissions are preferred. Thus, the choice of error control techniques has been reduced to either error detection coding/retransmission or data feedback, both of which maintain a minimum error rate.

Comparing attributes of these two techniques, it becomes apparent that the primary distinction is in the method of error detection. The error detection code adds redundant bits to the data bits for evaluation of the channel at the receiver station. In contrast, data feedback returns the data bits to the source station for channel evaluation. The effectiveness of error detection coding/retransmission will be dependent on the channel error rate, the coding redundancy, and the error detection probability of the code. In fact, the effectiveness for a block code will approach that of data feedback as shown in Appendix B. Thus, data feedback provides the effectiveness of the coding technique without the need for encoding and decoding hardware. Data feedback will be the preferred method of error control.

The extreme reliability obtained with data feedback constrains the throughput rate to a maximum of one-half the signalling rate. The estimated 6% bus time-occupancy would allow up to 8 round-trip transmissions per block transfer. The minimum block length of 40 bits would have an outputted error rate of 10^{-25} for a channel error rate of 10^{-3} with the probability of 1, 2, or 3 transmissions being 0.92, 0.9936, and 0.9995 respectively. The probability of 7 or more transmissions is less than $3X10^{-7}$. Thus, the 1MBPS signalling rate will provide sufficient reserve capacity to ensure correct data is reliably outputted at a high confidence level.

The selection of data feedback for error control is consistent with current Apollo practice. A specific example that comes to mind is the voice relaying of a critical information pad from mission control to the spacecraft. The pad data is voiced uplink, copied, and then voiced downlink where it is checked-off against the original. In essence, a digital mechanization of the same technique is recommended for the GN&C system data bus.

Although it would be desirable to provide the lowest channel error rate possible, an effective error control technique will tolerate a reduction in channel performance requirements. The lesser requirements allow consideration of simpler signalling techniques than the carrier systems discussed in 4.2. The next section will evaluate the suitability of a baseband system.

4.4 Baseband Signalling

The basic binary pulse waveforms are referredto as baseband signals. Two particular waveforms of interest here are the ON-OFF or unipolar pulse and the bipolar pulse. The data transmissions could consist of either the baseband signals or a carrier wave modulated by the baseband signals. The channel error rate of several binary data or keyed carrier techniques were listed in Table 12 for a white, Gaussian channel. The bit error rate expressions for coherent detection of baseband transmissions in a white, Gaussian channel are

- Unipolar pulse: $P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E/4}{2No}}$
- Bipolar pulse: $P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E/2}{2No}}$.

Thus, the bipolar pulse will provide the error rate of a unipolar pulse for 3 db less average signal energy per noise power per unit bandwidth, E/No, (6 db less peak signal energy). The lower error rate and elimination, or at least attenuation, of the d.c. component in the pulse spectrum favor the bipolar pulse compared to the unipolar pulse.

A fixed error rate comparison between the bipolar baseband and carrier transmissions in Table 12 reveals that ASK with coherent detection will require 3 db less E/No while binary PSK will require 6 db less E/No. It should be noted that the baseband noise bandwidth will be $\frac{1}{2}$ the noise bandwidth of either ASK or PSK. Consequently, the error rate performance as a function of signal/noise power ratio will be identical for bipolar baseband, coherent ASK, and PSK transmissions in a white, Gaussian channel.

The channel qualification was included to emphasize the basis of comparison. It is quite probable that a carrier channel will be realistically modeled as a white, Gaussian channel. It is unlikely that a baseband channel could be similarly characterized as evidenced by the M.S.F.C. EMC specification (Ref. 16).

The specification allows interference power spectra that decrease at a rate of $1/f$ to $1/f^2$ out to about 1-2 MHz and then become white. In addition, compatibility is required with inductive coupling of power lines and in presence of power line transients characterized by 50 volt peak amplitude pulses of 10 microseconds width and a repetition rate of 60-400 PPS. The low frequency and harmonic content of these potential interference signals will coincide with the baseband signal spectrum. Since the signal/interference power ratio cannot be ascertained from the EMC specification alone, suitability of the baseband channel quality is uncertain.

In an attempt to resolve the issue, the channel error rate of binary PSK on a Gaussian channel in presence of interference is shown in Figure 15 (Ref. 17). The Figure shows an acceptable error rate of 10^{-10} could be obtained for signal/noise power in excess of 20 db for signal/interference power as large as 5 db. For a given amount of interference power, the error rate will be a minimum when the power is concentrated in a single interferer and will be a maximum when the interference power is uniformly distributed among several interferers (Ref. 18). Although these results were obtained for a PSK system, the arguments presented in the references seem to apply as well to coherent detection of a bipolar baseband signal. With this extrapolation, an acceptable baseband channel could probably be obtained with appropriate EMC precautions.

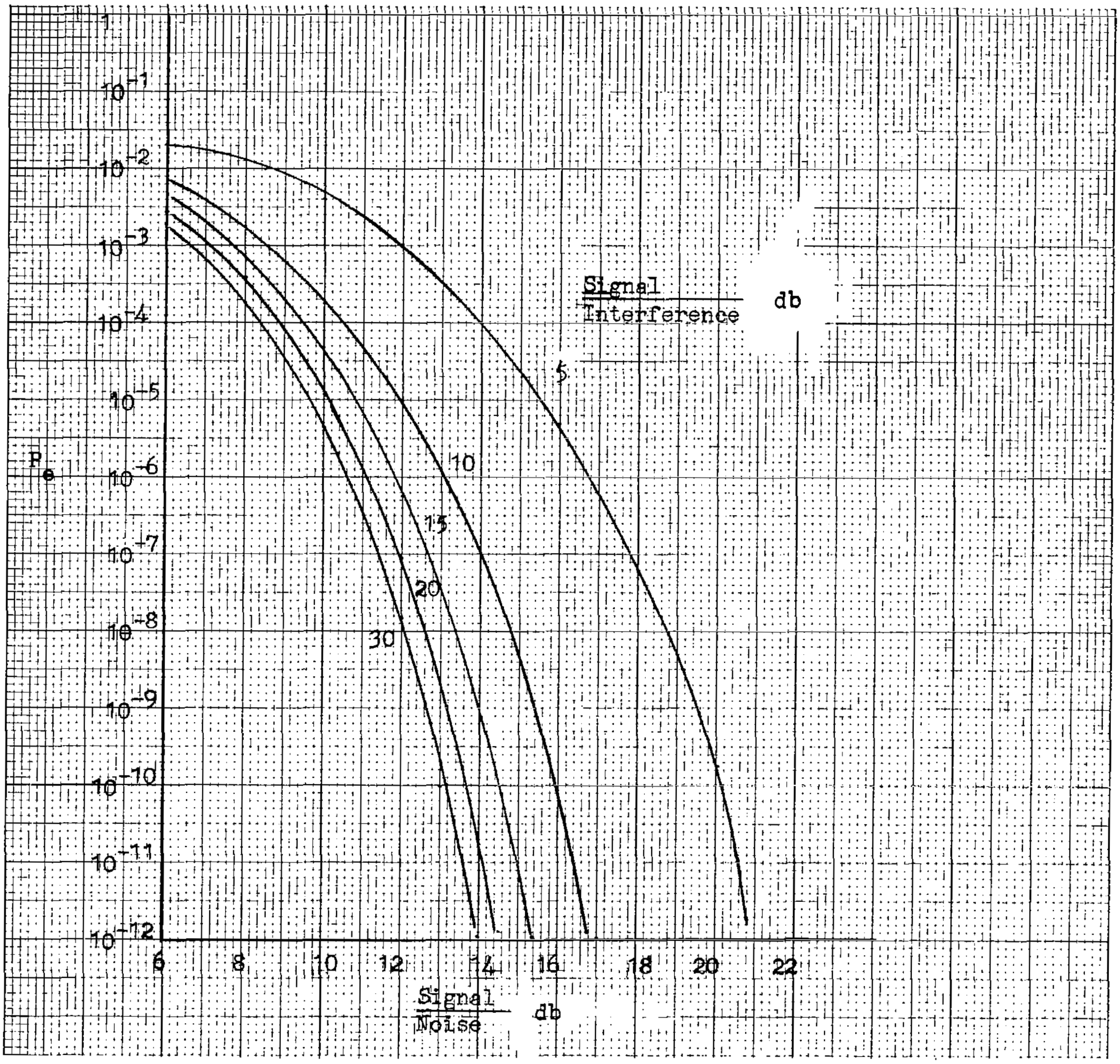


Figure 15.- Bit error probability for bi-phase PSK on a Gaussian channel with interference (ref. 17).

The selection of a signalling technique must compromise the conflicting objectives of lowest error rate and minimum hardware. The lowest possible error rate would be obtained with a PSK system. The simplicity of baseband transmission is preferred to any carrier transmission. The use of a coherent bipolar baseband system appears to be a reasonable compromise. If an acceptable baseband channel cannot be provided, carrier transmissions with center frequency at 2-3 MHz and 2 MHz channel bandwidth will be required.

The stated performance of bipolar baseband signalling was predicated on an optimum detection of each bit. This can be achieved with either correlation or matched filter techniques. For a rectangular pulse, the correlation detector and matched filter are identical and easily mechanized as an integrate and dump circuit. The detection process would consist of integrating the received signal during the bit period, sampling the integrator output at the end of the bit period, and deciding what symbol was transmitted on the basis of the sample polarity. The integrator would be discharged and the process repeated for the next bit.

An alternate method consists of shaping the received data pulse spectrum to provide regularly spaced nulls in the pre-detected signal time response. A thorough discussion is presented in Reference 19. A distinct advantage of this method is the reduction of high frequency components in the transmitted data pulse spectrum. The method should be considered further for its EMI advantages.

In either event, coherent detection will require a bit sync. The bit sync could be encoded or multiplexed with the data and transferred in the data channel or assigned to an auxiliary channel as a pilot carrier. A return-to-zero bipolar pulse essentially time multiplexes a bit sync for each data bit. The self-clocking feature and identical channel phase delay of the data bit and its sync would be desirable. The data baseband spectrum of this pulse would be 2 MHz wide as opposed to the 1 MHz bandwidth of a non-return-to-zero pulse.

A distinct disadvantage of multiplexing the sync onto the data channel is the implicit requirement for a clock in each station. Transmission of the data processor clock in an auxiliary channel would provide bit sync and serve as a continuous master timing signal for station functions as discussed in paragraph 2.8. Service as a coherent reference will impose limits on the allowable phase delay and its variation between the data and auxiliary channels. A sinusoidal 1 MHz clock would require a narrow bandwidth auxiliary channel located at the first null in the baseband spectrum.

The continuous master timing and elimination of redundant station clocks favor use of an auxiliary channel. The auxiliary channel could also be used to convey the special signals discussed in paragraph 3.4. This possibility will be considered below.

4.5 Multiplex of Data Control Signals

The need to transmit special signals for data control was established in 3.4 These signals are syncs for bit, frame, and word control and an 'acknowledge/accept' (A/A) signal. The previous paragraph suggested use of a sinusoidal signal in an auxiliary channel to serve as a master clock and bit sync. The auxiliary channel will have to be restricted to transmissions originating in the data processor to prevent 'interference' with the timing reference and to avoid problems in identifying the transmitting source.

The frame sync will be a bi-level signal generated internal to the data processor. The discrete signal could be logically combined with a station address detection to either inhibit or enable an addressed station line driver to prevent unscheduled transmissions and to restrict bus access. The frame sync could be multiplexed onto the auxiliary channel by pulse amplitude modulation (PAM) of the clock signal. The carrier amplitude level could be detected by an envelope detector and applied to a threshold circuit. This method would provide a positive frame sync with a few electronic components.

The word sync is required only during data transmission to signify the first and last bit of each word. The word sync could be in the form of a comma-free code and multiplexed directly with the data. Codes exist that will detect and eventually correct an asynchronous state. This method is not preferred due to the encode and decode hardware required in all stations.

The existence of a continuous bit sync and a fixed data word length would allow a word sync to be generated locally at each station with a bit counter. The counter would have to be initialized with the first frame bit and maintain a proper count for the remainder of the frame. A reliable count can be expected since it is performed internal to a station. The method is preferred for its simplicity.

An alternate method would generate a master word sync in the data processor and multiplex it onto the auxiliary channel. The sync signal could be obtained from detected zero crossings of a 25 KHz sinusoid in each station. The sinusoid would amplitude modulate the clock signal to utilize the AM detector needed for the frame sync. The previous method is less complicated and would be favored.

The A/A signal must be generated at the source station which restricts it to the data channel. Thus, the A/A signal must have some unique characteristic from which it can be easily and reliably detected in the data bit stream. A special coded word could serve this purpose. However, the data stream would have to be continuously examined to detect the A/A code word. A more positive and reliable method would employ a tone burst at a convenient frequency. A tone could be derived from the bit sync in each station and would allow coherent detection.

The data and auxiliary channels could be frequency division multiplexed onto the transmission line. The bipolar baseband signal will have a power spectral density of the form

$$S_B(f) = T \left[\frac{\mathrm{Sin}(\pi f/f_s)}{\pi f/f_s}\right]^2$$

where $T = 1/f_s$.

The normalized function is plotted in Figure 16-A for a 1 MBPS signalling rate. The first spectral lobe contains 90% of the total pulse energy and 95% of the total harmonic power. Considering power line harmonics and the data pulse spectrum, a data channel bandpass from about 2KHz to perhaps 0.9 MHz may be a reasonable

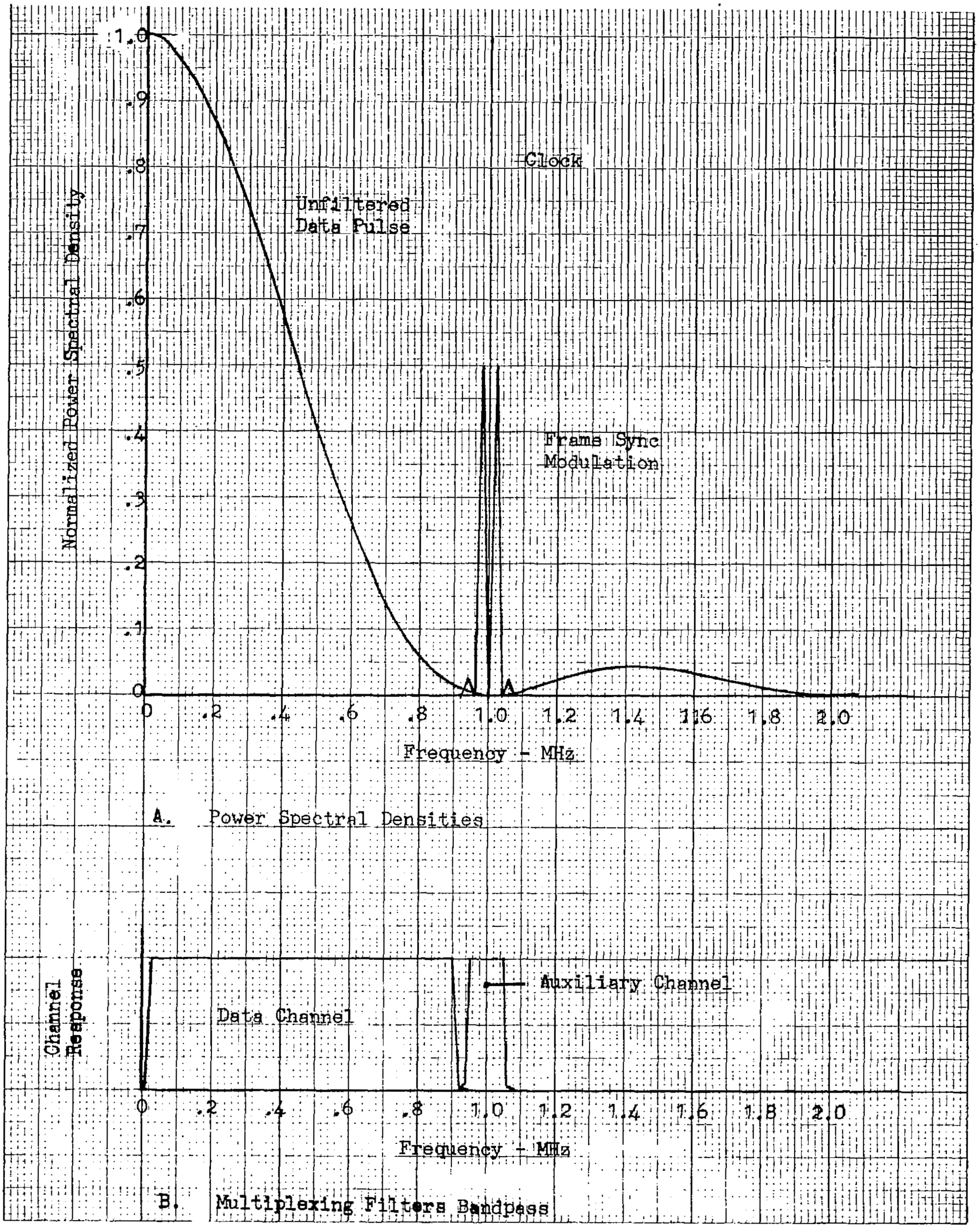


Figure 16.- Data and auxiliary channel multiplexing.

compromise in terms of amplitude and phase distortion of the received data pulse.

The auxiliary channel could be located in the data pulse spectrum null at 1 MHz. The clock signal would simply be a single spectral line at 1 MHz. The auxiliary channel bandwidth will be a compromise between the rise time of the detected frame sync and co-channel interference. The bandwidth would be on the order of 50 KHz to 100 KHz. The PAM spectrum could be estimated by assuming the frame intervals to be Poisson distributed. The minimum frame time would occur for a single round trip transmission of three words or about 120 microseconds. Thus, the frame signal rise time will be the prime consideration.

The multiplexed data and auxiliary channels would be as shown in Figure 16-B. The signals can be multiplexed differently than discussed here. The advantage of the particular methods described is their simplicity and the allocation of functions between data processor and addressable stations to minimize the station hardware.

4.6 Summary

The capability of data communication techniques to provide an acceptable word error rate with minimum hardware was evaluated. The acceptable word error rate was computed to be 10^{-10} for a criteria that allowed 1 word error to occur during a critical mission time period every 1000 missions. An average occurrence of 1 word error during 100-7 day missions and 1 word error during 2-30 day missions would be expected with this error rate.

The performance of keyed carrier systems was evaluated for a Gaussian channel and a noise burst channel. An acceptable bit error rate could be expected with any carrier system in a Gaussian channel. The bit error rate in a noise burst channel would not be dependable. The inability to reliably obtain an acceptable word error rate with a carrier system requires use of an error control technique.

Several error control techniques were discussed, evaluated, and compared. Techniques that employed repeat transmissions were preferred for their ability to maintain the probability of outputting correct information by lowering the throughput rate as channel quality degrades. A detailed comparison between error detection coding/retransmission and data feedback revealed their effectiveness would be similar. The data feedback technique is preferred since it provides effective error control without encoders and decoders in the stations.

Use of an error control technique reduces the channel error rate requirements which allows consideration of baseband signalling The quality of the baseband channel could not be predicted due to dependence on the EM environment and the equipment design. Although there is a justified concern, a coherent bipolar baseband system could provide acceptable performance. If a suitable baseband channel cannot be provided, a carrier system operating at 2 to 3 MHz with 2 MHz bandwidth would be required.

A method of multiplexing bit, frame, and word syncs and the special 'acknowledge/accept' signal was presented. An auxiliary channel for the bit and frame sync would also provide a continuous master clock to all stations. The data channel and auxiliary channel could be frequency division multiplexed onto a data bus line.

5. RECOMMENDATIONS

The previously stated objectives of this report were:

- Investigate GN&C System data requirements
- Determine required communication characteristics of the data bus
- Evaluate communication techniques compatible with the GN&C System requirements
- Recommend a data bus mechanization for the GN&C System.

The first three objectives were investigated and reported as three dependent but separable subjects; data requirements, data management and data communication techniques. These subjects encompass all aspects of data bus operation. The treatment of these subjects was organized for the orderly development of a data bus concept that would be subordinate to and compatible with the GN&C System, its functions, and its operations. The principal features and requirements of a data bus recommended from this study are summarized below.

5.1 Summary of Study Results

<u>System Data Requirements</u>

- The GN&C System will be composed of 7 sensor systems, 7 actuator systems, and 1 dedicated data processor.
- These systems will consist of 45 separate units on the MSC Orbiter Vehicle and can be grouped into 20 addressable stations.

- Local processors will be required to process 'raw' sensor data.
- A system total of 868 data words was estimated exclusive of FAULT data and local processor LOAD data.
- A 20 bit word will provide sufficient dynamic range and resolution of all transferred data.
- A maximum data rate of 55KBPS was estimated.
- The data rate will vary from 48.9 KBPS for Entry and Transition to 19.6 KBPS for Docking.
- A 1 MBPS signalling rate will provide sufficient data bus capacity.
- A central clock should be continuously provided to all stations.
- 'Elapsed time' and "Time to go' data words should be provided with 0.001 second time resolution for coordinating and evaluating events.

Data Management

- The data processor will control data bus access.
- Station to station data will be routed through the data processor.
- Data transfer will have a variable format and a pseudo-random schedule.
- A class organization of station data will facilitate the management, formatting, and transfer of data.
- A proposed organization consisted of MODE, INPUT, OUTPUT, STATUS, FAULT, and LOAD classifications.

- MODE data will include local editing flags and fault flag discretes to alert the data processor of an internal station change and a priority need to call specific data.
- The frequently transferred INPUT, OUTPUT and STATUS classes should consist of 6 to 10 data words for an efficient block transfer.
- Each station will respond only upon receiving a particular coded interrogate word.
- The interrogate word will be composed of a 5 bit binary station address, a 5 bit binary class address, and a 10 bit control instruction word.
- Buffer storage of all transferred data will be required.

Data Communication

- A word error rate of 10^{-10} will be acceptable.
- A noise burst channel should be anticipated.
- An error control technique will be required.
- Data feedback will be preferred for error control.
- Bipolar baseband signalling with coherent detection should provide acceptable performance.
- A simplex data channel will be sufficient.
- An auxiliary channel for a master clock, and the bit and frame syncs generated in the data processor will be required.
- Word sync derived locally from the bit sync will be sufficient.
- A special 'Acknowledge/Accept' control signal transmitted in the data channel will be required.
- The data and auxiliary channels will be frequency division multiplexed.

These recommendations can be implemented as discussed in the report. Although detailed circuit and hardware requirements were not always presented, they were included in the evaluation of alternate techniques. Since the evaluation criteria was to obtain acceptable performance with minimum hardware, the recommendations represent a compromise between these conflicting objectives.

5.2 A Data Bus Interface Assembly

A standard data bus interface to service all data bus users can be extracted from the text and recommendations. The functions allocated to the interface were indicated in Figures 6 and 7. The preferred implementation of these functions was presented in Section 4. The objective here will be to present an interface assembly that incorporates the recommendations and elaborate on certain areas.

A 'standard' interface would include only those functions common to all users. With this criteria, the standard interface would extend from the line coupling network to a level where the transmitted and received data stream are in identical form. A convenient interface with the station would be obtained at the level where the received and transmitted data have been formatted into a serial data stream. The resultant interface would not become involved in peculiar station data requirements since 'standard' signals would also interface with the station in parallel with the data stream for data control into and out of buffer storage. These arguments suggest the standard data bus interface functionally illustrated in Figure 17.

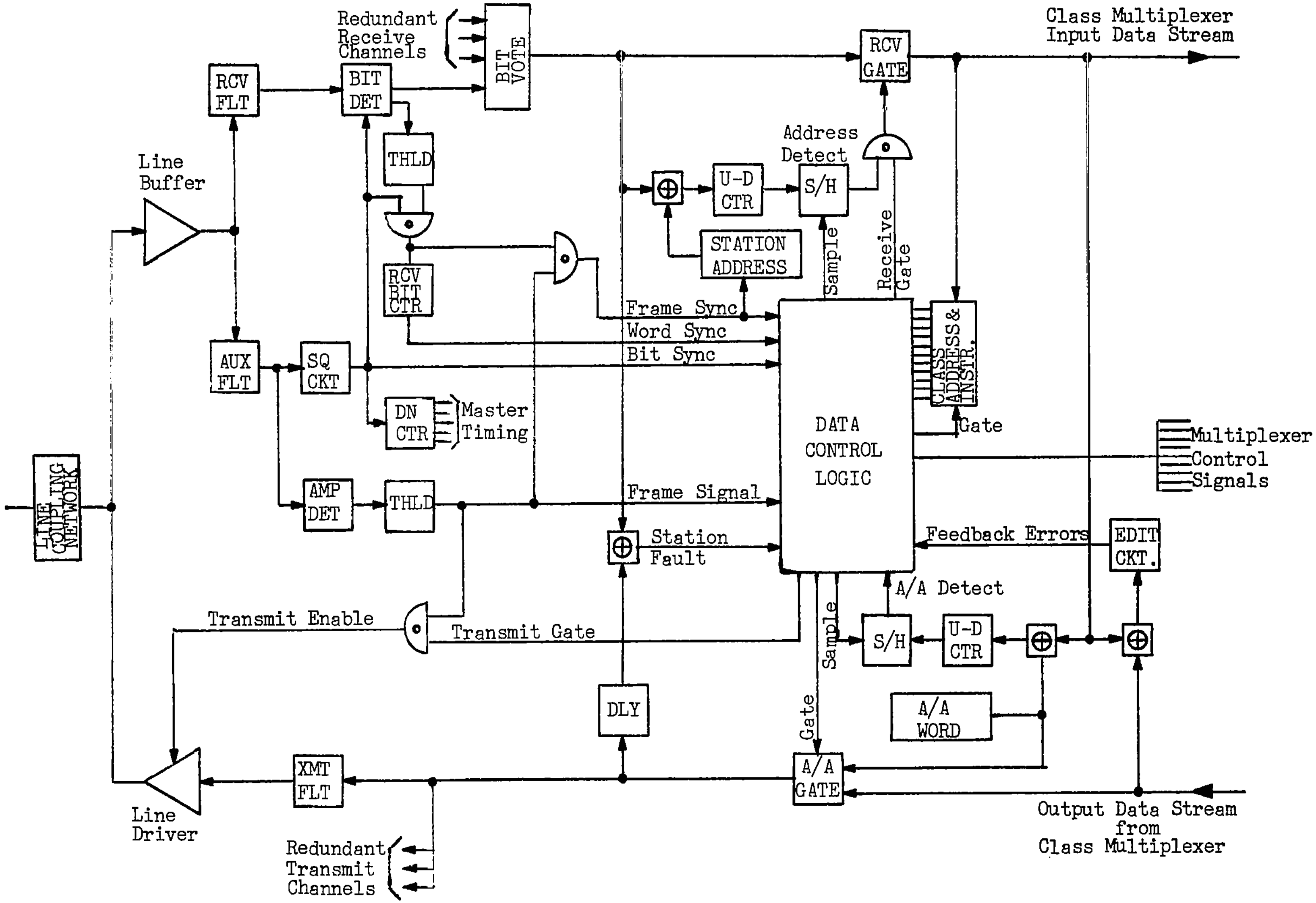


Figure 17.- A standard data bus interface assembly.

The illustration depicts a standard station interface. The data processor interface would require certain modifications that reflect its central authority. These modifications would consist of a pulse amplitude modulator for the clock and frame signals, the auxiliary channel line driver and bandpass filter, and minor changes to the station address detection circuitry and data control logic. Reference to Figure 7 should clarify the role of the proposed bus interface in relation to the class multiplexer and data storage.

Since the functional operations of the assembly was discussed intermittently in previous sections, a coherent discussion will be presented here to reveal certain features. The discussion will focus on the station interface from which the counterpart data processor interface operations can be inferred.

The line coupling network a.c. couples the redundant data bus lines into a line receiver and a line driver. The receiver is always active while the driver is gated on by the control logic only during a transmission. The received signal is frequency demultiplexed by the receive and auxiliary bandpass filters.

The auxiliary channel output is applied to the clock circuitry and the frame sync detector. The clock circuitry consists of a squaring circuit and a down counter. The squaring circuit strips off any AM and converts from bipolar to unipolar pulses by clamping the low level to ground. The resultant bit sync output would be buffered and applied to a bus for distribution. In addition, the bit sync would be divided down to derive master timing signals for all station operations. This operation could either be performed in the interface assembly as illustrated or internal to the station.

The frame sync detector consists of an amplitude detector and threshold. Absence of a frame signal resets appropriate circuits and inhibits the line driver. The detected frame signal is synced with the first received data bit thru a logical AND to initiate the station address detection.

The received data is applied to the bit detector which consists of an integrate and dump circuit. Unipolar pulses would be outputted for compatibility with station circuitry. Each bit would be detected by a threshold circuit, combined with bit sync, and counted to derive word sync. The received data pulses could be 'voted' with other channels at this point and will be discussed later. In either event, the data stream is applied to the station address detector and a receive gate.

The station address detector performs a cross-correlation between the received data and stored station address employing an exclusive-OR, an up-down counter, and a sample/hold circuit. The first frame word is the interrogate word consisting of station address bits, class address bits, and class instruction bits in that order. Hence, a perfect correlation sampled after the fifth frame bit would be a positive station detection. If the desired correlation is not obtained, additional station activity is inhibited until a frame signal reset. This feature provides a secure bus to the addressed station for the duration of the frame signal. The station detection is combined with a control logic signal to enable the receive gate to pass the received data stream. The remainder of the interrogate word is shifted into storage and read by the control logic.

The control logic generates required gating and control signals to execute the received instructions for the addressed class. If the instruction designates input data, the data stream is clocked into buffer storage via the class and word multiplexers. An 'input only' instruction would terminate with detection of the end of block transmission. An 'input then output' instruction would require the data to be recalled from storage and transmitted. The recall would commence with detection of the end of block transmission. An A/A word would be inserted in the stream after the last data word. Following its transmission, the line driver would be inhibited and the receive gate enabled. As discussed elsewhere, reception of a single A/A word after the feedback transmission would command acceptance of the data and terminate the transmission cycle. Reception of two consecutive A/A words would command rejection of the data, and initialize the assembly for the repeat transmission.

Instructions that designate output data would be similarly treated 'Output data only' would call data from the addressed class, transmit it, insert the A/A word, and terminate the instruction activity. An 'output then input' instruction would extend these activities to receive and process the feedback transmission. This would require recall from data storage in sync with the received data stream at the bit comparator. The bit comparator would consist of an exclusive-OR and perhaps a bit error counter or circuitry to edit for 'significant' bit errors. The comparator output at the end of block transmission would command either acceptance or rejection thru transmission of one or two A/A words, respectively.

The end of block transmission can be identified by the A/A word. A correlation of each received word with the stored A/A word similar to the station address detector would provide a positive detection.

A data transmission requires the control logic to generate a receive gate inhibit signal. The inhibit signal complement is applied to an AND with the frame signal to enable the line driver. This feature allows the data processor to 'clear' the bus by simply removing the frame signal.

Since the receiver remains active during transmission, a self-test feature can be simply provided by comparing the transmitted bits to the received bits. As illustrated, the transmitted bits would be synced with the received bits by a fixed delay. An exclusive-OR would provide fault detection. The self-test feature could also be incorporated in the data processor interface for both, the data channel and auxiliary channel.

Fault tolerance and redundancy have been considered indirectly in this report by recommending minimum hardware. The use of redundant data bus lines is a certainty. Some means of combining the redundant channels should be employed to indicate a faulty line and perhaps improve the effective received bit error rate. A majority vote was considered elsewhere and is suggested in the Figure. Another method that offers unique attributes is outlined below.

The information in a bipolar data pulse is determined by the bit detector from the data pulse phase. This characteristic suggests summing data pulses received from all redundant lines prior to bit detection. Perhaps the summing operation can be designed into the receive filter employing pulse transformers. The resultant channel sum signal would be inputted and processed by the bit detector with the following advantages:

1) The channel sum signal would provide better error performance than a single channel signal for two reasons; the resultant pulse energy is greater and independent line bursts are averaged with all line noise.
2) An operation similar to a majority vote would be realized without specific hardware for this capability.
3) Essentially ideal fault tolerance is obtained without the need for detection and switching.

These advantages are somewhat dependent on the amplitude and phase distortion of the data pulse as well as differential line delays. These areas should be investigated to exploit the unique advantages.

5.3 Future Activity

The report developed a data bus concept that included specific recommended features and techniques. These recommendations justify a hardware program. The objective of the program should be to:

- o Implement the recommended techniques.
- o Perform laboratory tests to determine the word error performance in quiet, Gaussian, and noise burst channels.
- o Conduct an EMC test in compliance with MSFC-Spec-279.

The test results would provide useful data for evaluation of the recommended techniques and reveal the suitability of a baseband channel. In addition, the program would provide an in-house baseline data bus for comparative evaluation of other proposed systems.

Concurrent with the hardware program, additional studies should be conducted to resolve issues that were not addressed in this report. This effort should investigate the following areas:

1. Tolerable limits of amplitude and phase distortion of the received data pulse.
2. The allocation of filtering between the transmit and receive filters.
3. Circuit and system redundancy.
4. The optimum block length as a function of channel burst characteristics.

5. The possibility of employing some redundant lines for the data feedback channel.
6. Potential advantages in assigning encoding and decoding requirements to the local processor.

The first, three items will be required for a hardware program. The remaining items should be evaluated for potential improvements in data bus capability and performance.

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APPENDIX A

APOLLO/LM GN & C SYSTEM SIGNALS

The initial approach to obtain data estimates for the SSV was to compile detailed signal lists for an actual spacecraft. The lists would be modified by appropriate deletions and additions to obtain a baseline system for the SSV. The Apollo/LM spacecraft was selected as a base because its capability was nearest that required for the SSV. During the meticulous compiling of the signal lists, it became apparent that the planned approach required many assumptions and a prolonged effort to obtain the LM data in a form compatible with data bus operation. Significance of the expected results would be similar to those more rapidly obtained by direct estimation. Thus, the approach was terminated. At the time of termination, useful information had been obtained and is reported in this Appendix.

The signal lists were compiled from Grumman Aircraft Engineering Corporation, Level 3 drawings of the LM-4 vehicle. Separate lists were compiled for each GN & C assembly and consist of identification of the interconnecting assembly, the Grumman signal title, and a signal category. Each signal was assigned to one of the following categories:

1) Timing (T) - signals employed for clock, sync, phase reference, etc.
2) Digital (D) - signals in any pulse or digital form
3) Analog (A) - signals in analog form
4) Control Discretes (C) - bi-level signals for command, control, monitor, etc.

Power lines were not tabulated. However, power lines that enabled an assembly to standby, operate, or self-test status were tabulated as control discretes. Other qualifications of these lists are:

1) BTME and GSE signals were not included.
2) The D and C, PANEL, IS, and CS lists include only those signals from the GN & C assemblies.
3) The PANEL list is a composite of all panel assemblies.
4) The IS list includes CWEA and PCMTEA signals as well as IS signals.

The assembly signal lists are presented as Tables A-1 through A-27. The signals of interest for the SSV are the intersystem signals obtained by combination of the assembly lists. The particular combinations of LM assemblies used to form equivalent SSV systems are listed in Table A-28. The resultant quantity of intersystem signals is illustrated in Table A-29. For the 11 systems listed, a total of 732 intersystem signals were tabulated; 34 timing signals, 100 digital signals, 203 analog signals, and 395 control discretes. It should be noted that these data accurately describe the LM spacecraft since no assumptions were employed. The systems listed should be reasonably equivalent to a corresponding SSV system except for the optical system which will be more complex on the SSV.

The LM data can be arranged in a form compatible with a data bus operation by classifying each intersystem signal as being either MODE, INPUT, OUTPUT, or STATUS as outlined in the text of this report. Note that here the MODE data will not include the flag discretes and that status discretes were included by assigning an appropriate number of 16 bit words to the STATUS data. If all system signals are assumed routed through the computer, the requirements of a LM data bus would be as presented in Figures A-1 and A-2. The quantity of signals from each system and their origin or destination are noted along a row. For example, the LM optical system would require 3 data words; 1 MODE word and 2 OUTPUT words. These data would be transferred to the LGC for storage as 1 MODE word and 2 INPUT words. The remaining systems are similarly treated. The quantity of signals involved and their distribution are clearly noted in Figure A-2. A total of 377 words are transferred between the GN & C systems and the computer. 62 of these words are stored within the computer. 70 of these words are looped through the computer. The remaining 245 words are combined with 30 computer generated words and transferred to the Flight Control, Instrumentation, and Communication Systems. (Note that the uplink and downlink data between the Computer and Communication System were not included.)

The distribution of these data words is significant and can be used as a guide for SSV use as indicated by the following examples. The quantity of data words handled at the computer is split 58% to the GN & C Systems and 42% to the Flight Control, Instrumentation, and Communication Systems. The distribution supports arguments for providing independent data busses for the GN & C System and the Command/ Display System on the SSV. The distribution of GN & C System data is 25% computer data and 19% system to system data, while 56% of the data is basically for display and monitor functions within the Flight Control and Instrumentation Systems. These percentages correspond reasonably well to estimates of the SSV data requirements presented elsewhere in this report.

-COMPUTER-

Subsystem	SYSTEM/LGC	SYSTEM/SYSTEM	SYSTEM/FLIGHT CONTROLS	SYSTEM/INSTRUMENTATION	SYSTEM/COMMUNICATION
OPTICAL 1-0-2-0	1-2-0-0				
LANDING RADAR 2-0-6-8	1-3-0-1		1-3-0-3	0-0-0-4	
RENDEZVOUS RADAR 2-2-19-7	1-2-0-1	0-8-0-0 (To Inertial)	1-9-2-2	0-0-0-4	
INERTIAL 2-18-23-7	1-9-8-4	0-0-8-0 (From RR) 0-3-0-0 (To AGS)	1-11-2-0	0-0-0-3	
ABORT GUIDANCE 3-9-15-11	1-0-0-0	0-0-3-0 (From Inertial) 0-6-0-0 (To RCS) 1-0-6-1 (To Rocket)	1-9-0-4		0-0-0-6
REACTION CONTROL 6-28-7-66	1-0-16-1	0-0-6-0 (From AGS) 1-2-6-1 (To Rocket)	4-5-0-5	0-0-0-59	
ROCKET PROPULSION 8-41-20-64	1-0-7-1	1-6-0-1 (From AGS) 1-6-2-1 (From RCS)	3-6-32-3	0-0-0-58	2-2-0-0
(Total: 24-98-92-163)	3-9-16-2	LGC Generated	2-16-8-1	1-0-0-1	0-0-1-0
Total:	(10-25-47-10)		(13-59-44-18)	(1-0-0-129)	(2-2-1-6)

FLIGHT CONTROLS 13-59-44-18

INSTRUMENTATION 1-0-0-129

COMMUNICATION 2-2-1-6

(Total: 16-61-45-153)

NOTE: Quantity of data words listed in following order: (MODE-INPUT-OUTPUT-STATUS)

Figure A-1.- Quantity of data words by type for a LM data bus.

	-COMPUTER- SYSTEM/LGC	SYSTEM/SYSTEM	SYSTEM/FLIGHT CONTROLS	SYSTEM/ INSTRUMENTATION	SYSTEM/ COMMUNICATION	
OPTICAL 3	3					
LANDING RADAR 16	5		7	4		FLIGHT CONTROLS 134
RENDEZVOUS RADAR 30	4	8	14	4		
INERTIAL 50	22	11	14	3		INSTRUMENTATION 130
ABORT GUIDANCE 38	1	17	14		6	
REACTION CONTROL 107	18	16	14	59		COMMUNICATION 11
ROCKET PROPULSION 133	9	8	44	58	4	Total: 275
	62	70	107	128	10	Distribution or Signals from GN&C Sys.
Total: 377	30	-	27	2	1	LGC generated signals
	92	70	134	130	11	Total system signals

Figure A-2.- Quantity of data words for a LM data bus.

Table A-1. AOT/CCRD SIGNALS

LGC

mark reset	C
mark x	C
mark y	C
mark reject	C

Sub-total: OT-OD-OA - 4C

Table A-2. RR SIGNALS

CDU (Signals on CDU list)

Sub-total: OT-OD-8A-OC

LGC

range gate strobe	T
range rate gate strobe	T
reset strobe	T
data flow	D
counter readout command	C
data good	C
power on/LGC mode	C
range low scale factor	C

Sub-total: 3T-1D-OA-4C

PANEL

transmitter power	A
RR AGC	A
shaft error	A
trunnion error	A
shaft axis designate	A
trunnion axis designate	A
RR self test enable	C
trunnion manual slew	C
shaft manual slew	C
+ supply/slew fast	C
+ supply/slew slow	C
-supply/slew fast	C
-supply/slew slow	C
manual mode	C
no track signal	C
mode select (manual/LGC)	C
auto angle track enable	C

Sub-total: OT-OD-6A-11C

Table A-2. RR SIGNALS (continued)

D & C

range display shift pulses (52.8KPPS)	T
display timing pulses	T
transponder mode serial range data	D
range rate (PPS)	D
1X Sin shaft	A
1X Sin trunnion	A
LOS shaft angle rate	A
LOS trunnion angle rate	A
doppler (range rate) sense	C

Sub-total: 2T-2D-4A-1C

IS

operational temp. 1	A
operational temp. 2	A
operational temp. 3	A
no track indication	C

Sub-total: OT-OD-3A-1C

Table A-3. SCA SIGNALS

CDU

trunnion CDU fine error	A
shaft CDU fine error	A
OG CDU fine error	A
MG CDU fine error	A
IG CDU fine error	A
IG CDU coarse error	A
MG CDU coarse error	A
OG CDU coarse error	A
shaft CDU coarse error	A
trunnion CDU coarse error	A
1X Sin AIG	A
1X Cos AOG	A
1X Sin AOG	A
1X Cos AMG	A
1X Sin AMG	A
1X Cos AIG	A
1X Sin trunnion	A
1X Cos trunnion	A
1X Sin shaft	A
1X Cos shaft	A
OG AC DAC output	A
MG AC DAC output	A
IG AC DAC output	A

Sub-total: OT-OD-23A-OC

PSA

800Hz 5% Phase A	T
800Hz 5% Phase B	T
800Hz 1% supply	T
3.2KHz feedback	T
IG torque motor voltage	A
MG torque motor voltage	A
OG torque motor voltage	A
IG torque motor current	A
MG torque motor current	A
OG torque motor current	A
IG servo amp test input	A
MG servo amp test input	A
OG servo amp test input	A
IRIG IG error	A
IRIG MG error	A
IRIG OG error	A

Table A-3. SCA SIGNALS (continued)

+D28 IMU operate	C
+D28 IMU standby	C
800Hz P.S. temp	C
Sub-total: 4T-0D-12A-3C	

<u>IMU</u>

PIPA temp. low	C
PIPA temp. high	C
IRIG temp. low	C
IRIG temp. high	C
IMU heater off	C
Heater temp. sensor	C
IMU blower off	C
Sub-total: 0T-0D-0A-7C	

<u>PTA</u>

X PIPA S/G output	D
Y PIPA S/G output	D
Z PIPA S/G output	D
PIPA cal. mod. temp.	A
Sub-total: 0T-3D-1A-0C	

<u>LGC</u>

3.2KPPS	T
Uplink '1'	D
Uplink '0'	D
ACE bias for LGC 14V	A
ACE bias for LGC 4V	A
LGC temp.	A
inhibit power fail	C
LGC operate	C
Sub-total: 1T-2D-3A-2C	

Table A-4. CDU SIGNALS

SCA (Signals on SCA list)

Sub-total: OT-OD-23A-OC

PSA

800Hz 1%	T
IG coarse align error	A
MG coarse align error	A
OG coarse align error	A
IG IX resolver signal for IMU cage	A
MG IX resolver signal for IMU cage	A
OG IX resolver signal for IMU cage	A
coarse align command	C
+D28 IMU operate	C
IMU cage override	C

Sub-total: 1T-OD-6A-3C

IMU

1X Sin AIG	A
1X Cos AIG	A
1X Sin AMG	A
1X Cos AMG	A
1X Sin AOG	A
1X Cos AOG	A
16X Sin AIG	A
16X Cos AIG	A
16X Sin AMG	A
16X Cos AMG	A
16X Sin AOG	A
16X Cos AOG	A

Sub-total: OT-OD-12A-OC

RR

1X Sin shaft	A
1X Cos shaft	A
1X Sin trunnion	A
1X Cos trunnion	A
16X Sin shaft	A
16X Cos shaft	A
16X Sin trunnion	A
16X Cos trunnion	A

Sub-total: OT-OD-8A-OC

Table A-4. CDU SIGNALS (continued)

LGC

51.2 KPPS	T
$+\Delta\theta c$ IG CDU drive pulses	D
$-\Delta\theta c$ IG CDU drive pulses	D
$+\Delta\theta c$ MG CDU drive pulses	D
$-\Delta\theta c$ MG CDU drive pulses	D
$+\Delta\theta c$ OG CDU drive pulses	D
$-\Delta\theta c$ OG CDU drive pulses	D
$+\Delta\theta c$ trunnion CDU drive pulses/+lateral velocity	D
$-\Delta\theta c$ trunnion CDU drive pulses/-lateral velocity	D
$+\Delta\theta c$ shaft CDU drive pulses/+forward velocity	D
$-\Delta\theta c$ shaft CDU drive pulses/-forward velocity	D
$+\Delta\theta t$ trunnion	D
$-\Delta\theta t$ trunnion	D
$+\Delta\theta t$ shaft	D
$-\Delta\theta t$ shaft	D
+Pitch ($\Delta\theta g$) pulses +Y	D
-Pitch ($\Delta\theta g$) pulses -Y	D
+Roll ($\Delta\psi g$) pulses +Z	D
-Roll ($\Delta\psi g$) pulses -Z	D
+Yaw ($\Delta\phi g$) pulses +X	D
-Yaw ($\Delta\phi g$) pulses -X	D
display inertial data	C
ISS coarse align enable	C
ISS CDU zero	C
ISS error angle counter enable	C
RR error angle counter enable	C
RR CDU zero	C
IMU operate discrete	C
IMU CDU fail	C
RR CDU fail	C

Sub-total: 1T-20D-0A-9C

PANEL

shaft angle error command	A
trunnion angle error command	A

Sub-total: 0T-0D-2A-0C

Table A-4. CDU SIGNALS (continued)

D & C

forward velocity	A
lateral	A
Ey pitch error (IG AC DAC output)	A
Ez roll error (MG AC DAC output)	A
Ex yaw error (OG AC DAC output)	A

Sub-total: 0T-0D-5A-0C

AEA

CDU zero 51.2KPPS	T
$+\Delta\theta g$ IG	D
$-\Delta\theta g$ IG	D
$+\Delta\theta g$ MG	D
$-\Delta\theta g$ MG	D
$+\Delta\theta g$ OG	D
$-\Delta\theta g$ OG	D

Sub-total: 1T-6D-0A-0C

Table A-5. PSA SIGNALS

SCA (Signals on SCA list)

Sub-total: 4T-OD-12A-3C

CDU (Signals on CDU list)

Sub-total: 1T-OD-6A-3C

IMU

800 Hz 5% Phase A	T
800 Hz 5% Phase B	T
800 Hz 1%	T
3.2K Hz PIPA and IRIG ref.	T
3.2K Hz feedback	T
IG error	A
MG error	A
OG error	A
IG torque motor	A
MG torque motor	A
OG torque motor	A
IMU temp. within limits	C
+D28 IMU operate	C
+D28 IMU standby	C

Sub-total: 5T-OD-6A-3C

PTA

+D28 IMU operate	C
Pulse torque P.S. inhibit	C

Sub-total: OT-OD-OA-2C

LGC

3.2 KPPS set	T
3.2 KPPS reset	T
800 PPS set	T
800 PPS reset	T
25.6 KPPS sync	T
ISS turn on delay complete	C
ISS turn on delay request	C
IMU temp. within limits	C
IMU cage discrete	C
IMU fail	C

Sub-total: 5T-OD-OA-5C

Table A-5. PSA SIGNALS (continued)

PANEL

IMU standby	C
IMU operate	C
IMU cage command	C

Sub-total: OT-OD-OA-3C

DSKY

pulse torque P.S. inhibit	C

Sub-total: OT-OD-OA-1C

Table A-6. IMU SIGNALS

SCA (Signals on SCA list)

Sub-total: OT-OD-OA-7C

CDU (Signals on CDU list)

Sub-total: OT-OD-12A-OC

PSA (signals on PSA list)

Sub-total: 5T-OD-6A-3C

PTA

+Tx PIPA	D
-Tx PIPA	D
+Ty PIPA	D
-Ty PIPA	D
+Tz PIPA	D
-Tz PIPA	D
+Tx IRIG	D
-Tx IRIG	D
+Ty IRIG	D
-Ty IRIG	D
+Tz IRIG	D
-Tz IRIG	D
X PIPA error	D
Y PIPA error	D
Z PIPA error	D

Sub-total: OT-15D-OA-OC

D & C

Sin AIG	A
Cos AIG	A
Sin AMG	A
Cos AMG	A
Sin AOG	A
Cos AOG	A

Sub-total: OT-OD-6A-OC

Table A-7. PTA SIGNALS

<u>SCA</u> (Signals on SCA list)

Sub-total: 0T-3D-1A-0C

<u>PSA</u> (Signals on PSA list)

Sub-total: 0T-0D-0A-2C

<u>IMU</u> (Signals on IMU list)

Sub-total: 0T-15D-0A-0C

<u>LGC</u>

PIPA interrogate pulse	T
PIPA switching pulse	T
PIPA data pulse	T
12.8 KPPS P.S. sync	T
Torque set	T
Torque reset	T
$+\Delta\theta x$	D
$-\Delta\theta x$	D
$+\Delta\theta y$	D
$-\Delta\theta y$	D
$+\Delta\theta z$	D
$-\Delta\theta z$	D
$-\Delta Vx$	D
$+\Delta Vx$	D
$-\Delta Vy$	D
$+\Delta Vy$	D
$-\Delta Vz$	D
$+\Delta Vz$	D
gyro torque enable	C

Sub-total: 6T-12D-0A-1C

Table A-8. LR SIGNALS

LGC

range gate strobe	T
reset strobe	T
XA velocity gate strobe	T
YA velocity gate strobe	T
ZA velocity gate strobe	T
data flow	D
counter readout command	C
range low scale factor	C
velocity data good	C
range data good	C
antenna position #1 indication (descent)	C
antenna position #2 indication (hover)	C

Sub-total: 5T-1D-0A-6C

PANEL

velocity transmitter power monitor	A
range transmitter power monitor	A
landing radar self test	C
antenna position #1 command	C
antenna position #2 command	C

Sub-total: 0T-0D-2A-3C

D & C

VXA range rate (PRF)	D
high range PRF	D
low range PRF	D
VYA analog (lateral velocity)	A
VZA analog (forward velocity)	A
V[illegible]A [illegible] signal	C
ant[illegible] position #1 indication	C

Sub-total: 0T-3D-2A-2C

Table A-8. LR SIGNALS (continued)

<u>IS</u>

operational temp. #1	A
operational temp. #2	A
operational temp. #3	A
power on indication	C
velocity data no good	C
range data no good	C
antenna position #1 indication	C
antenna position #2 indication	C

Sub-total: OT-OD-3A-5C

Table A-9. LGC SIGNALS

AOT/CCRD (Signals on AOT/CCRD list)

Sub-total: 0T-0D-0A-4C

SCA (Signals on SCA list)

Sub-total: 1T-2D-3A-2C

CDU (Signals on CDU list)

Sub-total: 1T-20D-0A-9C

PSA (Signals on PSA list)

Sub-total: 5T-0D-0A-5C

PTA (Signals on PTA list)

Sub-total: 6T-12D-0A-1C

RR (Signals on RR list)

Sub-total: 3T-1D-0A-4C

LR (Signals on LR list)

Sub-total: 5T-1D-0A-6C

PANEL

+ rate of descent	C
- rate of descent	C
rate of descent reset	C
TTCA translation switch enable	C
TTCA translation switch disable	C
yaw pulse command	C
pitch pulse command (LPD elevation)	C
roll pulse command (LPD azimuth)	C
descent engine override (gimbal off)	C

Sub-total: 0T-0D-0A-9C

Table A9. LGC SIGNALS (continued)

TTCA

+Z translation command	C
-Z translation command	C
+Y translation command	C
-Y translation command	C
+X translation command	C
-X translation command	C

Sub-total: 0T-0D-0A-6C

DSKY

800 Hz power sync	T
OUTO 1 thru 15	15D
key code 1 thru 5	5D
temperature caution	C
operator error	C
verb/noun flash	C
LGC warining	C
key release	C
uplink activity	C
RR lots enable lock-on	C
standby light	C
LR position command	C
restart	C
computer activity	C
ISS warning	C
caution light reset	C
standby/proceed	C
keyboard reset	C

Sub-total: 1T-20D-0A-15C

D & C

altitude rate	D
stage verified	C
display inertial data	C

Sub-total: 0T-1D-0A-2C

Table A-9. LGC SIGNALS (continued)

S & C

yaw rate command	D
pitch rate command	D
roll rate command	D
increase throttle	D
decrease throttle	D
DAP in control	C
in auto throttle	C
out of detent	C
attitude hold mode	C
auto mode	C
auto engine on command (AE or DE)	C
auto engine off command (AE or DE)	C
engine armed	C
start abort stage program	C
start abort program	C
gimbal off	C

Sub-total: 0T-5D-0A-11C

DECA

roll gimbal trim	D
pitch gimbal trim	D
apparent gimbal fail	C

Sub-total: 0T-2D-0A-1C

ATCA

thruster commands Iu, d, s, f,	4D
thruster commands II u, d, s, f,	4D
thruster commands III u, d, s, f,	4D
thruster commands IV u, d, s, f	4D

Sub-total: 0T-16D-0A-0C

RCS

thruster fail I u and f	C
thruster fail I d and s	C
thruster fail II d and f	C
thruster fail II u and s	C
thruster fail III d and f	C
thruster fail III u and s	C
thruster fail IV u and f	C
thruster fail IV d and s	C

Sub-total: 0T-0D-0A-8C

Table A-9. LGC SIGNALS (continued)

AEA

AGS initialization (down link data)	C

Sub-total: 0T-0D-0A-1C

IS

1.024 x 10^6 PPS clock (sync signal)	T
bit sync pulse	T
downlink data	D
downlink stop	C
downlink start	C

Sub-total: 2T-1D-0A-2C

CS

uplink '0'	D
uplink '1'	D

Sub-total: 0T-2D-0A-0C

Table A-10. PANEL SIGNALS*

<u>CDU</u>

OT-OD-2A-OC

<u>PSA</u>

OT-OD-OA-3C

<u>RR</u>

OT-OD-6A-11C

<u>LR</u>

OT-OD-2A-3C

<u>LGC</u>

OT-OD-OA-9C

<u>TTCA</u>

OT-OD-3A-OC

<u>ACA</u>

OT-OD-3A-18C

<u>DSKY</u>

OT-OD-OA-2C

<u>D & C</u>

(not determined)

<u>S & C</u>

OT-OD-OA-45C

<u>DECA</u>

OT-OD-1A-1C

<u>DE</u>

OT-OD-OA-10C

<u>AE</u>

OT-OD-OA-6C

<u>ATCA</u>

OT-OD-OA-4C

<u>RCS</u>

OT-OD-2A-60C

Table A-10. PANEL SIGNALS (continued)

RGA

OT-OD-3A-OC

AEA

OT-OD-OA-6C

IS

(not determined)

CS

(not determined)

*Signals are listed on specified assemblies.

Table A-11. TTCA

LGC

(Signals on LGC list)

Sub-total: OT-OD-OA-6C

PANEL

Z translation command	A
Y translation command	A
X translation command	A

Sub-total: OT-OD-3A-OC

Table A-12. ACA SIGNALS

PANEL

pulse yaw axis command	A
pulse pitch axis command	A
pulse roll axis command	A
thruster secondary coil I u, d, s, f	4C
thruster secondary coil II u, d, s, f,	4C
thruster secondary coil III u, d, s, f,	4C
thruster secondary coil IV u, d, s, f	4C
ACA 4 jet enable	C
ACA 4 jet disable	C

Sub-total: OT-OD-3A-18C

S & C

CDR yaw rate command	A
CDR pitch rate command	A
CDR roll rate command	A
SE yaw rate command	A
SE pitch rate command	A
SE roll rate command	A
CDR out of detent	C
SE out of detent	C

Sub-total: OT-OD-6A-2C

RCS

thruster secondary coils I u, d, s, f	4C
thruster secondary coils II u, d, s, f	4C
thruster secondary coils III u, d, s, f	4C
thruster secondary coils IV u, d, s, f,	4C

Sub-total: OT-OD-OA-16C

CS

CDR PTT switch	C
SE PTT switch	C

Sub-total: OT-OD-OA-2C

Table A-13. DSKY SIGNALS

PSA

pulse torque P.S. inhibit	C

Sub-total: 0T-0D-0A-1C

LGC

(Signals on LGC list)

Sub-total: 1T-20D-0A-15C

PANEL

RR auto angle track enable command	C
LR antenna position command	C

Sub-total: 0T-0D-0A-2C

IS

ISS warning	C
LGC warning	C

Sub-total: 0T-0D-0A-2C

Table A-14. D & C SIGNALS*

<u>CDU</u>	OT-OD-5A-OC
<u>IMU</u>	OT-OD-6A-OC
<u>RR</u>	2T-2D-4A-1C
<u>LR</u>	OT-3D-2A-2C
<u>LGC</u>	OT-1D-OA-2C
<u>PANEL</u>	(not determined)
<u>S & C</u>	OT-OD-6A-1C
<u>ATCA</u>	OT-OD-OA-3C
<u>AEA</u>	2T-2D-7A-OC
<u>IS</u>	(not determined)
<u>CS</u>	(not determined)

*Signals are listed on specified assemblies.

Table A-15. ATCA SIGNALS

LGC

(Signals on LGC list)

Sub-total: 0T-16D-0A-0C

PANEL

+D28 enable 12 jet	C
+D28 enable 4 jet	C
X translation/2 thruster select	C
deadband select	C

Sub-total: 0T-0D-0A-4C

D & C

yaw RGA signal	A
pitch RGA signal	A
roll RGA signal	A

Sub-total: 0T-0D-3A-0C

S & C

(Signals on S & C list)

Sub-total: 0T-0D-3A-13C

DECA

(Signals on DECA list)

Sub-total: 0T-0D-2A-0C

RCS

thruster primary commands I, u, d,s, f	4C
thruster primary commands II u, d, s, f,	4C
thruster primary commands III u, d, s, f,	4C
thruster primary commands IV u, d, s, f	4C

Sub-total: 0T-0D-0A-16C

Table A-15. ATCA SIGNALS (continued)

RGA		
	yaw rate signal	A
	pitch rate signal	A
	roll rate signal	A
	Sub-total: 0T-0D-3A-0C	
AEA		
	yaw attitude error	A
	pitch attitude error	A
	roll attitude error	A
	Sub-total: 0T-0D-3A-0C	
IS		
	1600 PPS	T
	pitch logic input error	D
	roll logic input error	D
	yaw logic input error	D
	pitch attitude error	A
	roll attitude error	A
	yaw attitude error	A
	pitch RG signal	A
	roll RG signal	A
	yaw RG signal	A
	X translation command	A
	Y translation command	A
	Z translation command	A
	RGA spin motor line A-B	A
	RGA spin motor line B-C	A
	RGA spin motor line C-A	A
	+D15 supply	A
	-D15 supply	A
	+D4.3 supply	A
	+D6 supply	A
	-D6 supply	A
	-D4.7 primary	A
	-D4.7 backup	A
	deadband select	C
	+D28 enable	C
	thruster primary commands I u, d, s, f,	4C
	thruster primary commands II u, d, s, f,	4C
	thruster primary commands III u, d, s, f,	4C
	thruster primary commands IV u, d, s, f,	4C
	Sub-total: 1T-3D-19A-18C	

Table A-16. S & C SIGNALS

LGC

(Signals on LGC list)

Sub-total: OT-5D-OA-11C

PANEL

thruster secondary coils I u, d, s, f	4C
thruster secondary coils II u, d, s, f	4C
thruster secondary coils III u, d, s, f	4C
thruster secondary coils IV u, d, s, f	4C
yaw pulse command	C
pitch pulse command	C
roll pulse command	C
direct yaw command	C
direct pitch command	C
direct roll command	C
ACA 4 jet enable	C
ACA 4 jet disable	C
start abort program	C
ACA out of detent	C
PNGS mode control/auto	C
PNGS mode control/attitude hold	C
AGS mode control/auto	C
AGS mode control/attitude hold	C
PNGS in use/ACA out of detent followup	C
Z translation command	C
Y translation command	C
X translation command	C
+D28 descent engine control	C
+D28 engine arm	C
+D28 engine fire	C
engine start	C
engine gimbal off	C
deadband select	C
+D28 abort stage	C
X translation/2 jet	C
descent engine override (on)	C
engine stop	C

Sub-total: OT-OD-OA-45C

Table A-16. S & C SIGNALS (continued)

ACA

(Signals on ACA list)

Sub-total: OT-OD-6A-2C

D & C

Ex	A
Ey	A
Ez	A
Ex display	A
Ey display	A
Ez display	A
stage verify status	C

Sub-total: OT-OD-6A-1C

DECA

increase throttle	D
decrease throttle	D
descent engine thrusting	A
auto thrust disable	C
analog trim mode	C
manual descent engine stop	C
manual descent engine start	C
engine gimbal off	C
auto descent engine on	C
auto descent engine off	C
+D28 interlock	C

Sub-total: OT-2D-1A-8C

DE

pre-valve power	C
TAC power	C
engine TAC auto command	C
engine TAC manual command	C
SOV power/redundant feed	C
SOV power/engine start	C

Sub-total: OT-OD-OA-6C

Table A-16. S & C SIGNALS (continued)

AE

solenoid valve A	C
solenoid valve B	C
ascent engine on command	C

Sub-total: OT-OD-OA-3C

ATCA

pitch rate command	A
roll rate command	A
yaw rate command	A
yaw mode control	C
roll mode control	C
pitch mode control	C
+D28 enable (DAP)	C
pulsed yaw command	C
pulsed pitch command	C
pulsed roll command	C
X translation command	C
Y translation command	C
Z translation command	C
+D28 descent start enable	C
pitch/roll 2 thruster select	C
ascent/descent select	C

Sub-total: OT-OD-3A-13C

AEA

Ex	A
Ey	A
Ez	A
Ex display	A
Ey display	A
Ez display	A
Auto engine on command	C
Auto engine off command	C
ascent engine on	C
descent engine on	C

Sub-total: OT-OD-6A-4C

Table A-16. S & C SIGNALS (continued)

IS

yaw pulse direct	C
pitch pulse direct	C
roll pulse direct	C
ACA outoof detent	C
PGNS mode select/auto	C
PGNS mode select/attitude hold	C
AGS mode select/auto	C
AGS mode select/attitude hold	C
auto engine on command	C
auto engine off command	C
abort stage command	C
ascent engine on/off	C
descent engine on	C
engine fire override	C

Sub-total: 0T-0D-0A-14C

CS

CDR umbilical	A
SE umbilical	A

Sub-total: 0T-0D-2A-0C

Table A-17. RCS SIGNALS

LGC

(Signals on LGC list)

Sub-total: OT-OD-OA-8C

PANEL

propellant quantity/system A	A
propellant quantity/system B	A
Typical for systems A, B:	
ox main SOV open command (1)	2C
fuel main SOV open command (1)	2C
ox main SOV closed indication (1)	2C
fuel main SOV closed indication (1)	2C
Typical for systems A, B and feeds 1, 2:	
ox feed open command (1)	4C
fuel feed open command (1)	4C
ox feed closed indication (1)	4C
fuel feed closed indication (1)	4C
ox crossfeed valve open command	C
fuel crossfeed valve open command	C
ox crossfeed valve closed indication	C
fuel crossfeed valve closed indication	C
Typical for valves A, B and quads I, II III, IV:	
ox isolation valve open (1)	8C
fuel isolation valve open (1)	8C
ox isolation valve close (1)	8C
fuel isolation valve close (1)	8C

Sub-total: OT-OD-2A-60C

ACA

(signals on ACA list)

Sub-total OT-OD-OA-16C

ATCA

(Signals on ATCA list)

Sub-total: OT-OD-OA-16C

Table A-17. RCS SIGNALS (continued)

<u>IS</u>

Typical for system A, B:	
He regulator pressure output monitor (1)	2A
He tank pressure (1)	2A
He tank temp. (1)	2A
ox manifold pressure (1)	2A
fuel manifold pressure (1)	2A
ox tank temp. (1)	2A
fuel tank temp. (1)	2A
Typical for quad I, II, III, IV:	
quad cluster temp. (1)	4A
u thrust chamber pressure (1)	4A
d thrust chamber pressure (1)	4A
s thrust chamber pressure (1)	4A
f thrust chamber pressure (1)	4A
Typical for system A, B:	
fuel primary interconnect valve not closed (1)	2C
fuel secondary interconnect valve closed (1)	2C
ox primary interconnect valve not closed (1)	2C
ox secondary interconnect valve not closed (1)	2C
fuel main SOV closed (1)	2C
ox main SOV closed (1)	2C
ox manifold feed not closed	C
fuel manifold feed not closed	C
Typical for valves A, B, and quad I, II, III, IV:	
ox isolation valve closed idication (1)	8C
fuel isolation valve closed indication (1)	8C

Sub-total: OT-OD-34A-30C

Table A-18. DECA SIGNALS

<u>LGC</u>

(Signals on LGC list)

Sub-total: OT-2D-OA-1C

<u>PANEL</u>

manual throttle command	A
descent engine arm	C

Sub-total: OT-OD-1A-1C

<u>S & C</u>

(Signals on S & C list)

Sub-total: OT-2D-1A-8C

<u>GDA</u>

pitch GDA extend	A
pitch GDA retract	A
pitch GDA position signal	A
roll GDA extend	A
roll GDA retract	A
roll GDA position signal	A

Sub-total: OT-OD-6A-OC

<u>DE</u>

auto throttle command	C
manual throttle command	C
descent engine arm	C
descent engine start	C

Sub-total: OT-OD-OA-4C

<u>ATCA</u>

pitch trim error	A
roll trim error	A

Sub-total: OT-OD-2A-OC

<u>AEA</u>

descent engine on	C

Sub-total: OT-OD-OA-1C

Table 18. DECA SIGNALS (continued)

<u>IS</u>

fail signal excitation	A
roll GDA position	A
pitch GDA position	A
descent engine arm	C
roll trim fail	C
pitch trim fail	C
auto thrust command	C
manual thrust command	C
roll GDA position retract/extend	C
pitch GDA position retract/extend	C

Sub-total: OT-OD-3A-7C

Table A-19. GDA SIGNALS

<u>DECA</u>

(Signals on DECA list)

Sub-total: OT-OD-6A-OC

Table A-20. DE SIGNALS

PANEL

open primary helium solenoid valve	C
close primary helium solenoid valve	C
closed primary helium solenoid valve inidication	C
open secondary helium solenoid valve	C
close secondary helium solenoid valve	C
closed secondary helium solenoid valve indication	C
fuel vent solenoid valve	C
fuel vent solenoid valve open indication	C
oxidizer vent solenoid valve	C
oxidizer vent solenoid valve open indication	C

Sub-total: OT-OD-OA-10C

S & C

(Signals on S & C list)

Sub-total: OT-OD-OA-6C

DECA

(Signals on DECA list)

Sub-total: OT-OD-OA-4C

IS

TAC TLM pot 1	A
TAC TLM pot 2	A
thrust chamber pressure	A
ox temp. 1	A
ox temp. 2	A
fuel temp. 1	A
fuel temp. 2	A
He pressure regulator out manifold	2A
ox pressure tank #1 ullage	2A
fuel pressure tank #1 ullage	2A
He supply tank redundant	2A
PQGS	2A
ox pressure engine interface	2A
fuel pressure engine interface	2A
pressure ambient He pre-pressure bottle	2A
pressure He regulator out manifold redundant	2A
pressure thrust chamber +D28	2A
pressure thrust chamber data	A

Table A-20. DE SIGNALS (continued)

<u>IS</u> (continued)

Typical valves A, B, C, D:

valve closed (1)	4C
valve not closed (1)	4C
valve open (1)	4C
valve not open (1)	4C

Sub-total: OT-OD-27A-16C

Table A-21. AE SIGNALS

PANEL

latch He solenoid valve 1 (primary) open	C
latch He solenoid valve 1 (primary) close	C
latch He solenoid valve 1 (primary) closed indication	C
latch He solenoid valve 2 (secondary) open	C
latch He solenoid valve 2 (secondary) close	C
latch He solenoid valve 2 (secondary) closed indication	C

Sub-total: OT-OD-OA-6C

S & C

(Signals on S & C list)

Sub total: OT-OD-OA-3C

IS

ox temp. tank	A
fuel temp. tank	A
regulator output manifold pressure	2A
ox tank level flow	2A
fuel tank level flow	2A
press ox isolation valve inlet	A
press fuel isolation valve inlet	A
press He supply tank 1	2A
press He supply tank 2	2A
temp. He supply tank 1	2A
temp. He supply tank 2	2A
thrust chamber pressure	A
redundant manifold pressure regulator out	2A
ox tank ullage pressure	2A
fuel tank ullage pressure	2A
He primary solenoid valve closed	C
He secondary solenoid valve closed	C

Typical for systems A, B and isolation, propellant valves:

valve open (1)	4C
valve not open (1)	4C
valve closed (1)	4C
valve not closed (1)	4C

Sub-total: OT-OD-25A-18C

Table A-22. DEDA SIGNALS

AEA

DEDA shift pulses	T
shift 4 bits out	T
shift 4 bits in	T
DEDA clock	T
DEDA address data	D
DEDA data	D
DEDA enter	C
DEDA readout	C
DEDA hold	C
DEDA clear	C

Sub-total: 4T-2D-0A-4C

Table A-23. RGA SIGNALS

<u>PANEL</u>

roll RG torque test	A
pitch RG torque test	A
yaw RG torque test	A

Sub-total: OT-OD-3A-OC

<u>ATCA</u>

(Signals on ATCA list)

Sub-total: OT-OD-3A-OC

Table A-24. ASA SIGNALS

<u>AEA</u>

128 KKPS	T
Δ Vx	D
ΔVy	D
ΔVz	D
$\Delta\int$P·dt	D
$\Delta\int$Q·dt	D
$\Delta\int$R·dt	D

Sub-total: 1T-6D-0A-0C

<u>IS</u>

+D28	A
+D12	A
ASA temp.	A
29 vrms 400Hz	A

Sub-total: 0T-0D-4A-0C

Table A-25. AEA SIGNALS

CDU

(Signals on CDU list)

Sub-total: 1T-6D-0A-0C

LGC

(Signals on LGC list)

Sub-total: 0T-0D-0A-1C

PANEL

standby	C
+D28 enable	C
start abort stage program	C
start abort program	C
automatic	C
PGNS in use/ACA out of detent followup	C

Sub-total: 0T-0D-0A-6C

D & C

altitude shift pulse	T
altitude rate shift pulse	T
altitude data	D
altitude rate data	D
lateral velocity	A
Sin α	A
Cos α	A
Sin β	A
Cos β	A
Sin α	A
Cos α	A

Sub-total: 2T-2D-7A-0C

S & C

(Signals on S & C list)

Sub-total: 0T-0D-6A-4C

DECA

(Signals on DECA list)

Sub-total: 0T-0D-0A-1C

Table A-25. AEA SIGNALS (continued)

<u>ATCA</u>

(Signals on ATCA list)

Sub-total: 0T-0D-0A-3C

<u>ASA</u>

(Signals on ASA list)

Sub-total: 1T-6D-0A-0C

<u>DEDA</u>

(Signals on DEDA list)

Sub-total: 4T-2D-0A-4C

<u>IS</u>

PGNS downlink stcp pulse	T
PGNS downlink bit sync pulses	T
AGS downlink bit sync pulses	T
AGS downlink stop pulse	T
AGS downlink data	D
AEA test fail	C

Sub-total: 4T-1D-0A-1C

Table A-26. IS SIGNALS*

RR	OT-OD-3A-1C
LR	OT-OD-3A-5C
LG LGC	2T-1D-OA-2C
PANEL	(not determined)
DSKY	OT-OD-OA-2C
D & C	(not determined)
S & C	OT-OD-OA-14C
DECA	OT-OD-3A-7C
DE	OT-OD-27A-16C
AE	OT-OD-25A-18C
ATCA	1T-3D-19A-18C
RCS	OT-OD-34A-30C
ASA	OT-OD-4A-OC
AEA	4T-1D-OA-1C
CS	(not determined)

*Signals are listed on specified assemblies.

Table A-27. CS SIGNALS*

<u>LGC</u>	OT-2D-OA-OC
<u>PANEL</u>	(not determined)
<u>ACA</u>	OT-OD-OA-2C
<u>D & C</u>	(not determined)
<u>S & C</u>	OT-OD-2A-OC
<u>IS</u>	(not determined)

*Signals are listed on specified assemblies.

Table A-28. SSV SYSTEMS AND EQUIVALENT LM ASSEMBLIES

SSV SYSTEM	LM ASSEMBLY (or system)
Optical System	AOT/CCRD
Rendezvous Radar	RR
Inertial System	SCA, CDU, PSA, IMU, PTA
Navigation Radar	LR
G N & C Data Processor	LGC
Flight Control System	PANEL, TTCA, ACA, DSKY, D & C
Reaction Control System	ATCA, S & C, RCS
Rocket Propulsion System	DECA, GDA, DE, AE, PQGS
Abort Guidance System*	DEDA, RGA, ASA, AEA
Instrumentation System**	IS
Communication**	CS

*No equivalent SSV system

**Not a part of G N & C system

TABLE A-29.- LM INTERSYSTEM SIGNALS

SYSTEM	OPTICAL	RENDEZ-VOUS RADAR	INERTIAL	NAVI-GATION RADAR	COMPUTER	FLIGHT CONTROL	REACTION CONTROL	ROCKET PROPULSION	ABORT GUIDANCE	INSTRU-MENTATION	COMMUN-ICATION	TOTAL SIGNALS
Optical					0-0-0-4							0-0-0-4
Rendezvous Radar			0-0-8-0		3-1-0-4	2-2-10-12				0-0-3-1		5-3-21-17
Inertial		0-0-8-0			13-34-3-17	0-0-13-4			1-6-0-0			14-40-24-21
Navigation Radar					5-1-0-6	0-3-4-5				0-0-3-5		5-4-7-16
Computer	0-0-0-4	3-1-0-4	13-34-3-17	5-1-0-6		1-21-0-32	0-16-0-8	0-7-0-12	0-0-0-1	2-1-0-2	0-2-0-0	24-83-3-86
Flight Control		2-2-10-12	0-0-13-4	0-3-4-5	1-21-0-32		0-0-2-83	0-0-13-65	2-2-10-6	0-0-0-2*	0-0-0-2	5-28-52-211
Reaction Control					0-16-0-8	0-0-2-83		0-0-5-13	0-0-6-0	1-3-53-48		1-19-66-152
Rocket Propulsion					0-7-0-12	0-0-13-65	0-0-5-13		0-0-6-5	0-0-55-55	0-0-0-2	0-7-89-152
Abort Guidance			1-6-0-0		0-0-0-1	2-2-10-6	0-0-6-0	0-0-6-5		4-1-4-1		7-9-26-13
Instru-mentation		0-0-3-1		0-0-3-5	2-1-0-2	0-0-0-2*	1-3-53-48	0-0-55-55	4-1-4-1		•	7-5-118-114
Communication					0-2-0-0	0-0-0-2*		0-0-0-2		*		0-2-0-4
Total Signals By Type	0-0-0-4	5-3-21-17	14-40-24-21	5-4-7-16	24-83-3-86	5-28-52-211	1-19-66-152	0-7-89-152	7-9-26-13	7-5-118-114	0-2-0-4	68-200-406-790**
Total Signals By Quantity	4	46	99	32	196	296	238	248	55	244	6	1464**

NOTES: Signal entries in following order (Timing-Digital-Analog-Control Discretes)

• Includes only G N & C assembly signals.

** Note that each signal has been counted twice in these totals.

APPENDIX B

A Probabilistic Analysis of Error Control Techniques

Many error control techniques have been proposed, employed and described in the literature. Selection of a particular technique is a difficult task that involves many complex considerations. The lack of a common performance measure and the limited perspective of each reported technique contribute to the task difficulty. The probabilistic analysis reported in this Appendix alleviates these difficulties and offers a convenient basis for evaluation of the effectiveness of error control techniques.

The motivation for employing error control is to increase the outputted data reliability from that achievable with the basic channel error rate. A rational criteria for selecting a particular technique would be to obtain the highest reliable information rate that involves the least equipment complexity. It is difficult to assign a common measure to equipment complexity since it is dependent on available devices, their reliability, and the designers ingenuity. However, a standard measure of effectiveness can be devised to allow judicious decisions between techniques.

An acceptable measure of effectiveness would certainly have to include, the quantity of information, the reliability of the information, and the total data transmission time. These factors suggest a figure of merit termed the reliable information rate that is defined as

$$F \triangleq \frac{\text{(number of correct information bits)(probability of outputting correct information)}}{\text{total data transmission time.}}$$

This measure will be determined from a probabilistic approach for the following error control techniques:

1. Majority vote of independent channels
2. Majority vote of redundant transmissions

3. Error Detection Coding
4. Error Correction Coding
5. Error Detection Coding/Retransmission
6. Data Feedback

To maintain perspective on the effectiveness of these techniques, the reliable information rate of direct data transmission will be used as a reference.

Probabilistic Approach

There are only three possibilities for received and processed data with the techniques under consideration:

- correct information is outputted - P_C
- incorrect information is outputted - P_I
- information is rejected. - P_R

These probabilities are determined by the following channel and processing characteristics:

- channel error probability - P_e
- channel error pattern statistics - $P(e,n)$
- error detection probability - P_d
- error correction probability - $P_c = P_{c/d} \cdot P_d$
- data block length - $n=m+k$
- information bits per block - m
- coding bits per block - k
- number of block transmissions - t

The probabilistic relations will be determined for a Gaussian channel where bit errors are independent and the probability of e or more errors in block length n is given by

$$P(e,n) = \sum_{i=e}^{n} \binom{n}{i} P_e^{\,i} \, (1-P_e)^{n-i}.$$

For small nP_e,

$$P(o,n) \approx 1-nP_e$$

$$P(e,n) \approx nP_e.$$

The approach could also be applied to a burst channel model but will not be reported here.

The detection and correction probabilities are dependent on the particular technique employed. When codes are used, P_d and P_c are functions of k, n, and P(e,n). Explicit relations between these variables are incalculable except for specific codes. However, bounded relations have been published. (Ref. 13, 15)

Direct Data Transmission

In direct data transmission, m bits are transmitted through the channel. Since there is no processing, the m bits are simply outputted either correct or incorrect dependent on the occurrence of bit errors. The probability tree of Figure B-1 illustrates the process. The probabilities are readily obtained and evaluated for the Gaussian channel.

$$P_C = P(o,m) \approx 1-mP_e$$

$$P_I = P(e,m) = 1-P(o,m) \approx mP_e$$

$$P_R = 0$$

and

$$\dot{F} = \frac{mP_c}{mT} = \frac{(1-mP_e)}{T}.$$

Majority Vote of Independent Channels

In this technique, m bits are simultaneously transmitted through a number of independent channels. The received bits are compared with a majority rule prior to output. For 3 channels, the effective outputted bit error rate will be

$$P_b = \sum_{i=2}^{3} \binom{3}{i} P_e^{\,i} (1-P_e)^{3-i} \approx 3P_e^{\,2}.$$

For an odd number of channels, there can be no indecision as illustrated in Figure B-2. Hence, the Gaussian channel probabilitites are

$$P_C = P(o,m) \approx 1-3mP_e^{\,2}$$

$$P_I = P(e,m) = 1-P(o,m) \approx 3mP_e^{\,2}$$

$$P_R = 0$$

and

$$F = \frac{mP(o,m)}{mT} \approx \frac{(1-3mP_e^{\,2})}{T}.$$

This technique functions to reduce the channel bit error rate with subsequent reduction in outputting incorrect information. An improvement factor of $3P_e$ is realized for three channels compared to direct data transmission.

Majority Vote of Redundant Transmissions

This technique achieves independent bit errors by redundantly transmitting the m bits through a single channel. The received bits are stored and then processed with a majority rule prior to output. The resultant probabilities are identical to those obtained from independent channels when the number of channels equals the number of redundant transmissions. Hence, for 3 transmissions

$$P_C = P(o,m) \approx 1-3mP_e^{\ 2}$$

$$P_I = P(e,m) \approx 3mP_e^{\ 2}$$

$$P_R = 0$$

and

$$F = \frac{m\ P(o,m)}{3mT} \approx \frac{(1-3mP_e^{\ 2})}{3T}.$$

Redundant transmissions also functions to reduce the channel bit error rate. The improvement is obtained by a corresponding reduction in throughput rate.

<u>Error Detection Coding</u>

m data bits are encoded with the insertion of k check bits to form a coded block of length n. The n bits are passed through the channel and decoded. The decoding policy rejects the data block when errors are detected and outputs the data when no errors are detected as illustrated in Figure B-3. Letting P_d be the probability of detecting all error patterns of e or less errors in a block length n,

$$P_C = P(o,n) \approx 1-nP_e$$

$$P_I = P(e,n)(1-P_d) \approx nP_e\ (1-P_d)$$

$$P_R = P(e,n)\cdot P_d \approx nP_e\cdot P_d$$

and

$$F = \frac{m\ P(o,n)}{nT} \approx \frac{(1-nP_e)}{(1+k/m)T}.$$

The technique provides no improvement in outputting correct information. Instead, a reduction in incorrect output information is obtained by rejecting the data block.

Error Correction Coding

Encoding the m data bits with an error correcting code of k check bits would be an improvement compared to error detection coding. The received n bits are decoded with a policy that 1) correctly outputs those data whose errors are within the code capability to detect and correct, 2) rejects those data with detectable but uncorrectable errors, or 3) incorrectly outputs those data with undetectable errors. The policy is shown in Figure B-4 where P_d is as previously defined and $P_{c/d}$ is the conditional probability of correcting errors that have been detected from which $P_c = P_{c/d} \cdot P_d$. The desired probabilities are expressed as

$$P_C = P(o,n) + P(e,n) \cdot P_d \cdot P_{c/d} \approx 1 - nP_e(1-P_c)$$

$$P_I = P(e,n)(1-P_d) \approx nP_e(1-P_d)$$

$$P_R = P(e,n) \cdot P_d \cdot (1-P_{c/d}) \approx nP_e(P_d - P_c)$$

and

$$F = \frac{1-nP_e(1-P_C)}{(1+k/m)T}.$$

The improvement is realized by correcting a fraction of the data that would have been rejected. The significance of the improvement compared to direct data transmission is entirely dependent on the code. In fact, improvement beyond direct data transmission is realized only when $P_c > k/n$. Otherwise, the increased errors due to code redundancy will exceed the error correction capability of the code.

Error Detection Coding/Retransmission

The use of an error detection code with correction by retransmission offers more improvement than obtainable from error correction coding. The error detection coding would be identical to that previously described with the decoding policy altered to request a block retransmission instead of rejection as shown in Figure B-5.

The probabilities for any single transmission are identical to those for error detection coding,

$$P_C' = (1-P_e)^n \approx 1-nP_e$$

$$P_I' = \lfloor 1-(1-P_e)^n \rfloor (1-P_d) \approx nP_e \ (1-P_d)$$

$$P_R' = \lfloor 1-(1-P_e)^n \rfloor P_d \approx nP_e \cdot P_d$$

The probability of exactly t transmissions is

$$P(t) = P_R'^{(t-1)}(1-P_R')$$

which decreases very rapidly for small nP_eP_d. The desired probabilities for t transmissions can be shown to be,

$$P_C(t) = \sum_{i=1}^{t} P_C' \, P_R'^{(i-1)} = P_C' \, \frac{(1-P_R'^{t})}{(1-P_R')}$$

$$P_I(t) = \sum_{i=1}^{t} P_I' P_R'^{(i-1)} = P_I' \quad \frac{1-P_R'^{t}}{1-P_e'}$$

$$P_R(t) = P_R'^{t}$$

Substitution of the primed quantities yields

$$P_C(t) \approx (1-nP_e) \left\lfloor \frac{1-(nP_eP_d)^{t})}{1-nP_eP_d} \right\rfloor$$

$$P_I(t) \approx nP_e(1-P_d) \left\lfloor \frac{1-(nP_eP_d)^{t})}{1-nP_eP_d} \right.$$

$$P_R(t) \approx (nP_eP_d)^{t}.$$

The retransmissions provide improvement by increasing the probability of a correct output while decreasing the probability of an incorrect output. The improvement can be substantial as demonstrated below. A conservative bound on the probability of detecting an error given that an error has occurred in a block code with k parity checks, would be

$$P_d \geq 1-2^{-k}.$$

Since $nP_e \ll 1$, $P_C(t)$ would rapidly converge to

$$P_C \approx \frac{1-nP_e}{1-nP_eP_d}.$$

With substitution of the bounded expression and algebraic manipulation,

$$P_C \approx \frac{1}{1+nP_e2^{-k}}.$$

Employing the identity $\frac{1}{1+X} = 1-X-X^2-X^3$,

$$P_C \approx 1-nP_e\cdot 2^{-k}.$$

The bounded probability of an incorrect output can be similarly obtained as

$$P_I \approx nP_e\cdot 2^{-k}.$$

Thus, retransmission offers an improvement relative to a direct transmission by a factor of $(1+k/m)2^{-k}$ for an error detecting block code. For a block length of 300 bits, including 30 check bits, and a $P_e = 10^{-5}$, $P_I \approx 3X10^{-12}$ for retransmission as opposed to $3X10^{-3}$ for direct transmission.

It should be noted that the throughput rate can be maximized by proper selection of block length as a function of channel error rate and the quantity of coding bits. The reliable information rate is

$$F(t) = \frac{mP_C(t)}{ntT} \approx \frac{(1-nP_e)\left[1-(nP_eP_d)^t\right]}{(1+k/m)tT(1-nP_eP_d)}.$$

Data Feedback

A comparison between the received data bits and corresponding transmitted data bits constitutes an ideal error detection method that can be approximated by employing data feedback. The process consists of assigning the m information bits to storage at the source as they are inserted into the channel. The received data would be placed in storage at the receiver station and then returned thru the channel to the source station. The stored bits are compared with corresponding returned bits and either causes a retransmission upon disagreement of one or more bits, or signals the receiver to accept its stored data. All errors incurred on the forward and feedback transmissions will be detected except when the feedback transmission errors are an exact complement of the forward transmission errors. The conditional probability of this event, given that errors occurred on both transmissions, for a data block length m is

$$P(e_1=\bar{e}_2) = \frac{1}{2^m}\cdot\frac{1}{2^m} = 2^{-2m}.$$

The probabilities for this process can be computed from Figure B-6. For a single round trip transmission,

$$P_C' = P^2(o,m) = (1-P_e)^{2m} \approx 1-2mP_e$$

$$P_I' = P^2(e,m)\cdot P(e_1=\bar{e}_2) = \left[1-(1-P_e)^{2m}\right]2^{-2m} \approx 2mP_e\cdot 2^{-2m}$$

$$P_R' = 1-P_C'-P_R' = \left[1-(1-P_e)^{2m}\right](1-2^{-2m}) \approx 2mP_e(1-2^{-2m})$$

The probability of exactly t round trip transmissions is

$$P(t) = P_R'^{(t-1)}\ (1-P_R') \approx 2mP_e^{(t-1)}$$

which decreases very rapidly. The desired probabilities for t transmissions are

$$P_C = \sum_{i=1}^{t} P_C P_R'^{(i-1)} = P_C' \left(\frac{1-P_R'^{t}}{1-P_R'}\right)$$

$$P_I = \sum_{i=1}^{t} P_I' P_R'^{(i-1)} = P_I' \left(\frac{1-P_R'^{t}}{1-P_R'}\right)$$

$$P_R = P_R'^{t}.$$

After substituting the primed relations for small mP_e and some manipulation,

$$P_C \approx \frac{(1-2mP_e)\left\lfloor 1-\{2mP_e(1-2^{-2m})\}^t\right\rfloor}{1-2mP_e(1-2^{-2m})}$$

$$P_I \approx \frac{(2mP_e)2^{-2m}\left\lfloor 1-\{2mP_e(1-2^{-2m})\}^t\right\rfloor}{1-2mP_e(1-2^{-2m})}$$

$$P_R = \{2mP_e(1-2^{-2m})\}^t.$$

For a block length of 300 bits and $P_e=10^{-5}$, $P_I \approx 6X10^{-183}$ for data feedback compared to $\approx 3X10^{-12}$ for retransmission and $\approx 3X10^{-3}$ for direct data transmission. The example illustrates the tremendous data reliability realized with data feedback. For the same example, $P_R \approx 6X10^{-3}$ for feedback and $\approx 3X10^{-3}$ for the retransmission technique. Thus, the prbability of only 1 transmission would be 0.994 and 0.997 for the respective techniques; an insignificant difference compared to the data reliability.

A comparison of either the exact or approximate expressions for data feedback with corresponding expressions for error detection coding/retransmission reveals an interesting fact. All expressions are exactly equivalent for an error detection code with

$P_d = 1-2^{-2m}$ and $m=k$.

It can be concluded that data feedback will provide better performance than a highly redundant error detection code without the need for encoders and decoders. The excellent performance coupled with elimination of encoders and decoders in all bus interfaces clearly indicates data feedback to be a preferred technique for high reliability on a Gaussian channel.

The reliable information rate is

$$F(t) \approx \frac{mP_C(t)}{2mtT} \approx \frac{(1-2mP_e)\lfloor 1-\{2mP_e(1-2^{-2m})\}^t \rfloor}{2tT\lfloor 1-2mP_e(1-2^{-2m})\rfloor}$$

and can be expanded to the following form for $2mP_e \ll 1$,

$$F(t) \approx \frac{(1-2mP_e 2^{-2m})\lfloor 1-\{2mP_e(1-2^{-2m}\}^t \rfloor}{2tT} .$$

As in the previous case, the maximum throughput rate will be obtained by proper choice of data block length for the particular channel error rate.

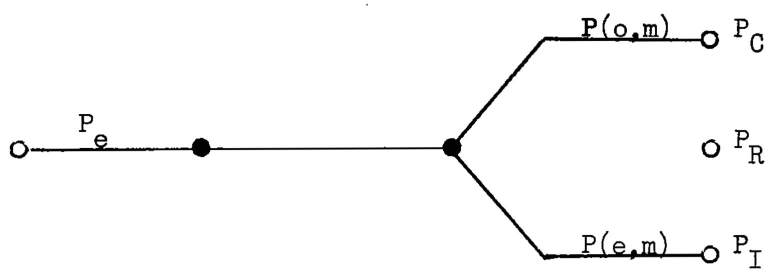

Figure B-1. Direct Data Transmission Probabilities

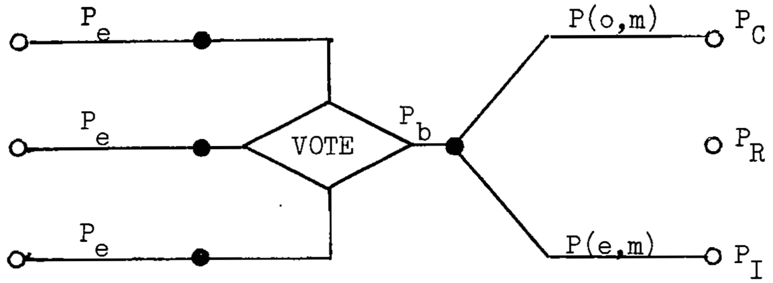

Figure B-2. Probabilities for Majority Vote of Independent Channels or Redundant Transmissions

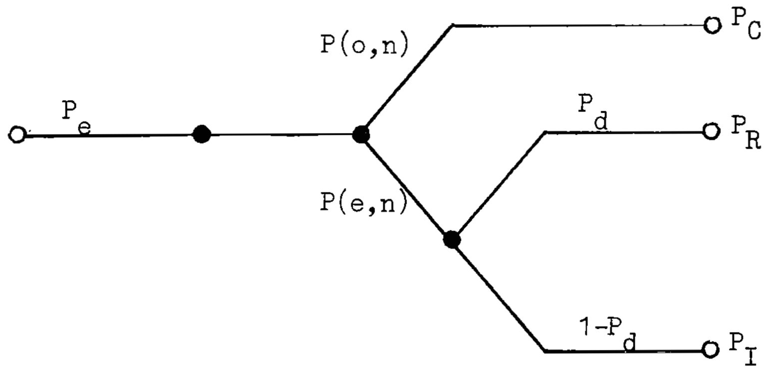

Figure B-3. Error Detection Coding Probabilities

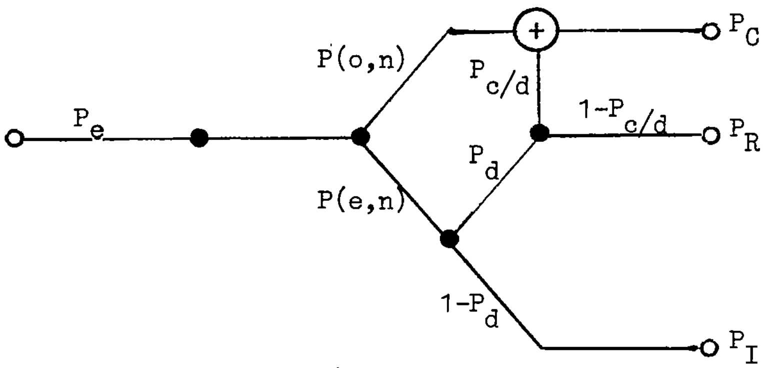

Figure B-4. Error Correction Coding Probabilities

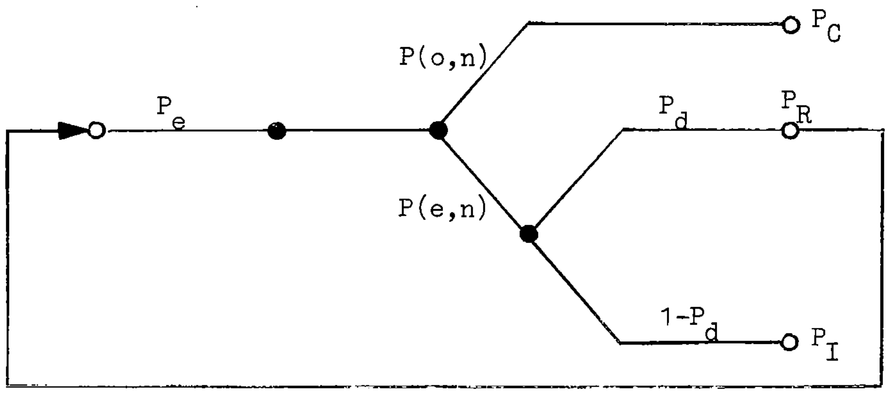

Figure B-5. Error Detection Coding/Retransmission Probabilities

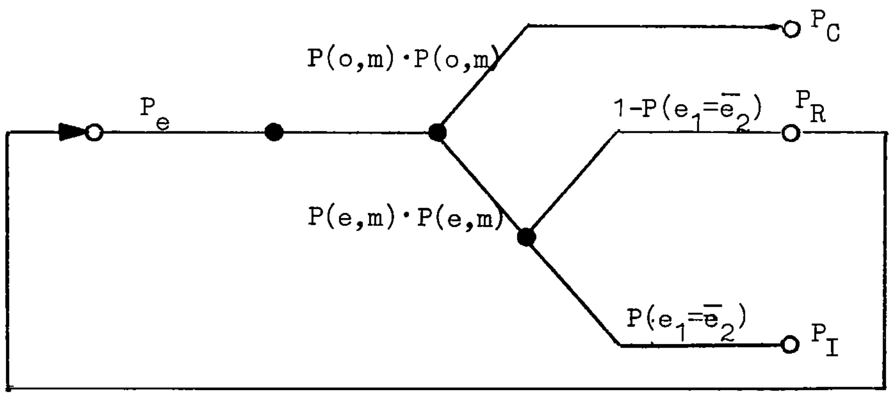

Figure B-6. Data Feedback Probabilities

NASA-Langley, 1971 —— 31